4. FINAL LIST OF ROUND TWO POLLUTANTS

This section presents the methods and the results of the Comprehensive Hazard Identification study, in which a quantitative risk assessment for the Highly Exposed Individual, including dose-response evaluation, exposure assessment, and risk characterization, is performed. The 31 pollutant candidates for the Round Two sewage sludge regulation, identified in the Preliminary Hazard Identification, are evaluated in this Comprehensive Hazard Identification. Note that in the Technical Support Documents for Round One, the calculations begin with an acceptable level of risk, and work backwards to determine what pollutant concentrations in the sewage sludge are acceptable for that use/disposal practice, thereby calculating pollutant limits. In this study, levels of risk that might be associated with a given pollutant under a given use/disposal practice are estimated, based on sewage sludge pollutant concentrations from the NSSS. Those pollutants/practices with high risk estimates are candidates for the final list of Round Two pollutants. The results of this Comprehensive Hazard Identification indicate that only a subset of the 31 pollutants should be considered for regulation in Round Two.

4.1 GENERAL APPROACH FOR THE COMPREHENSIVE HAZARD IDENTIFICATION

The purpose of the Comprehensive Hazard Identification study is to identify pollutants that warrant further consideration for the final list of Round Two pollutants. Analyses are performed to identify pollutants that may potentially cause human health or ecological risk for a Highly Exposed Individual (HEI). Consistent with the EPA Guidelines for Exposure Assessment (57 FR 22888, May 29, 1992), the risk to the HEI is estimated using a combination of high-end and average assumptions designed to give a plausible estimate of the individual risk at the upper end of the risk distribution (e.g., above the 90th percentile of the actual distribution).

In general for this study, high-end assumptions are used to characterize sewage sludge concentrations and certain exposure parameters, while average values are typically used to characterize use/disposal practices and soil and meteorological characteristics. Specifically, sewage sludge concentrations are based on the 95th percentile concentrations of pollutants obtained in the NSSS, with non-detects set equal to the minimum level (e.g., the minimum concentration of pollutant that could be measured) (see Exhibit 4-1). For each sewage sludge use/disposal practice, the HEI is defined as "an individual who remains for an extended period of time at or adjacent to the site where the maximum exposure occurs" (U.S. EPA, 1992a). Numerous exposure assumptions are specific to each exposure pathway and are given in the subsequent sections.[1]

This chapter describes the methods used for each sewage sludge use or disposal practice and exposure pathway (Section 4.2 (land application), 4.3 (surface disposal), and 4.4 (incineration)). Next, methods for estimating human health and ecological risk are presented

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More detailed explanations for the derivations of the specific values used in this study are provided in the Technical Support Documents for Round One (e.g., U.S. EPA, 1992a).

(Section 4.5). For those pollutant-exposure pathway combinations for which an exposure can be estimated, the calculated risk associated with that exposure is then presented. Based on these risk estimates, the pollutants that warrant further consideration for inclusion on the final list of Round Two pollutants are presented in Chapter 5.

EXHIBIT 4-1
95th Percentile Concentrations for Round Two Candidate Pollutants

Pollutant	95th Percentile Sewage Sludge Concentrations[1] (mg/kg dry weight)
Acetic acid (2,4-dichlorophenoxy)	0.030
Aluminum	36,400
Antimony	24
Asbestos[2]	Not Available
Barium	1,730
Beryllium	8
Bis(2-ethylhexyl)phthalate	191
Boron	182
Butanone, 2-	69.3
Carbon disulfide	3.13
Cresol, p-	306
Cyanides (soluble salts and complexes)	130
Dioxins and dibenzofurans	3.11×10^{-4}
Endosulfan-II	0.0667
Fluoride	411
Manganese	1,620
Methylene chloride	31.3
Nitrate	5,020
Nitrite	462
Pentachloronitrobenzene	0.0793
Phenol	57.5
Polychlorinated biphenyls -- coplanar[3]	5.4
Propanone, 2-	116
Propionic acid, 2-(2,4,5-trichlorophenoxy)	0.040
Silver	128

Pollutant	95th Percentile Sewage Sludge Concentrations[1] (mg/kg dry weight)
Thallium	10.6
Tin	138
Titanium	363
Toluene	238
Trichlorophenoxyacetic acid, 2,4,5-	0.0505
Vanadium	64.1

[1] Non-detects set equal to the Minimum Level. Concentrations from the NSSS.
[2] Asbestos was not tested in the NSSS, but is toxic, persistent, and may be in sewage sludge.
[3] Sewage sludge samples were not analyzed for coplanar PCBs in the NSSS. A composite PCB concentration was estimated by combining the concentrations of the seven Aroclor mixtures measured in the NSSS.

4.2 LAND APPLICATION PATHWAY EXPOSURE METHODOLOGIES

Methods were developed in Round One to evaluate risk from sewage sludge that is land-applied to agricultural and non-agricultural sites. These methods include evaluating both human health and ecological risks associated with exposure to sewage sludge through 14 different pathways. In Round Two, an additional exposure pathway, breastfeeding, is also considered. These 15 exposure pathways and the corresponding HEIs are summarized in Exhibit 4-2.

To estimate exposure to pollutants in sewage sludge that is land-applied, several non-pollutant-specific types of data are required, including information on application practices and soil characteristics. The average values used for these parameters are shown in Exhibit 4-3. The way in which these data were combined with pollutant-specific data to estimate exposure is described in Sections 4.2.1 through 4.2.15.

For both agricultural and non-agricultural land application sites, it is necessary to estimate the number of years that a site is used and the rate at which sewage sludge is applied to that site. An estimate of the depth to which sewage sludge is incorporated at the site also must be made. The values used for these parameters in this analysis are presented in Exhibit 4-3. Note that for the forest and public contact sites, depth of incorporation is assumed to be zero, and therefore the "soil concentration" of a pollutant is the same as the sewage sludge concentration.

For the soil at agricultural land and reclaimed sites, an average bulk density of 1600 kg/m^3 is assumed (U.S. EPA, 1992a). For the bulk density of sewage sludge-amended soil, an average value of 1400 kg/m^3 is assumed (U.S. EPA, 1992a). For natural "background" soil concentrations of inorganics, 90th percentile concentrations of inorganics in soil throughout the United States were used (U.S. Geological Survey, 1992). To ascertain whether sewage sludge pollutant concentrations were greater than natural soil concentrations, the 90th percentile soil concentrations were compared to the 95th percentile pollutant concentrations in sewage sludge. As shown in Exhibit 4-4, for three inorganics the 95th percentile sewage sludge concentrations are less than (aluminum and titanium) or approximately equal to (vanadium) the 90th percentile natural soil concentrations. This suggests that natural concentrations of these inorganics contribute significantly to the overall exposure of an HEI. For antimony and tin, sewage sludge concentrations are much greater than natural soil concentrations, indicating that sewage sludge loadings are the major determinant of an HEI's exposure to those inorganic pollutants. In this analysis, background concentrations of nitrate and nitrite are not applicable due to the cycling of nitrogen in soil systems. The background concentration of asbestos also is not applicable because asbestos would not be taken up by crops. Cyanide was the only applicable inorganic pollutant for which background soil concentration data were not available. For the organic pollutants, background concentration data are not required because it is assumed that there are not natural concentrations of organic pollutants in soil.

EXHIBIT 4-2
Definitions of Exposure Pathways and Highly Exposed Individuals (HEIs) for Land Application

Pathway	Agricultural HEI	Non-Agricultural HEI		
		Forest	Reclamation	Public Contact
1. Sewage Sludge → Soil → Plant → Human	Human ingesting crops grown on sewage sludge-amended agricultural land.	A person who regularly harvests wild plants from forest land amended with sewage sludge.	A person who regularly harvests wild plants from reclamation sites amended with sewage sludge.	A person who regularly harvests wild plants from public contact sites amended with sewage sludge.
2. Sewage Sludge → Soil → Plant → Human	Residential home gardener.	NA	NA	NA
3. Sewage Sludge → Human	Child between the ages of 1 and 6 who ingests sewage sludge from storage piles or the soil surface of agricultural land daily for 5 years.	Child between the ages of 4 and 6 who ingests sewage sludge from the soil surface of forest land daily for 2 years.	Child between the ages of 4 and 6 who ingests sewage sludge from the soil surface of a reclamation site daily for 2 years.	Child between the ages of 1 and 6 who ingests sewage sludge from the soil surface of a public contact site daily for 5 years.
4. Sewage Sludge → Soil → Plant → Animal → Human	Farm households producing a major portion of the animal products they consume. It is assumed that the animals eat plants grown in soil amended with sewage sludge.	A hunter of deer and elk that feed in forests. The hunter preserves meat for consumption throughout the year.	A hunter of deer and elk that feed on reclamation sites. The hunter preserves meat for consumption throughout the year.	NA
5. Sewage Sludge → Animal → Human	Farm households producing a major portion of the animal products they consume. It is assumed that livestock ingest sewage sludge while grazing.	Consumer of livestock that ingest sewage sludge in sewage sludge-amended forests.	Consumer of livestock that ingest sewage sludge in sewage sludge-amended reclamation sites.	NA

EXHIBIT 4-2

Definitions of Exposure Pathways and Highly Exposed Individuals (HEIs) for Land Application (cont'd.)

Pathway	Agricultural HEI	Non-Agricultural HEI		
		Forest	Reclamation	Public Contact
6. Sewage Sludge → Soil → Plant → Animal	Livestock ingesting crops grown on sewage sludge-amended agricultural land.	A small herbivore that lives its entire life in a sewage sludge-amended forest feeding on seeds and small plants; or, livestock that graze on grasses growing in a sewage-sludge amended forest.	Livestock that graze on grasses growing on sewage sludge-amended reclamation sites.	A small herbivore that lives its entire life in a sewage sludge-amended area feeding on seeds and small plants close to the sewage sludge-soil layer in a public contact site.
7. Sewage Sludge → Animal	Grazing livestock that ingest sewage sludge applied to agricultural land.	Grazing livestock that ingest sewage sludge applied to forest sites.	Grazing livestock that ingest sewage sludge applied to reclamation sites.	NA
8. Sewage Sludge → Soil → Plant	Plants grown on sewage sludge-amended agricultural land.	Plants grown in sewage sludge-amended soil in forests.	NA	Plants grown in sewage sludge-amended soil on public contact sites.
9. Sewage Sludge → Soil → Soil Organism	Earthworms living in sewage sludge-amended agricultural soil.	Earthworms living in sewage sludge-amended soil in forests.	Earthworms living in sewage sludge-amended soil on reclamation sites.	Earthworms living in sewage sludge-amended soil on public contact sites.
10. Sewage Sludge → Soil → Soil Organism → Soil Organism Predator	Insectivorous small mammals eating soil organisms living in sewage sludge-amended agricultural soil.	Insectivorous small mammals eating soil organisms that live in sewage sludge-amended soil in forests.	Insectivorous small mammals eating soil organisms that live in sewage sludge-amended soil on reclamation sites.	Insectivorous small mammals eating soil organisms that live in sewage sludge-amended soil on public contact sites.
11. Sewage Sludge → Soil → Airborne Dust → Human	Tractor operator exposed to dust while plowing large areas of sewage sludge-amended soil.	NA	NA	NA

EXHIBIT 4-2
Definitions of Exposure Pathways and Highly Exposed Individuals (HEIs) for Land Application (cont'd.)

Pathway	Agricultural HEI	Non-Agricultural HEI		
		Forest	Reclamation	Public Contact
12. Sewage Sludge → Soil → Surface Water → Human	Human who consumes both fish and water from a stream that receives eroded sewage sludge-amended soil from agricultural land.	Human who consumes both fish and water from a stream that receives eroded sewage sludge-amended soil from a forest.	Human who consumes both fish and water from a stream that receives eroded sewage sludge-amended soil from a reclamation site.	Human who consumes both fish and water from a stream that receives eroded sewage sludge-amended soil from a public contact site.
13. Sewage Sludge → Soil → Air → Human	Human breathing volatile pollutants from sewage sludge-amended agricultural land.	Human breathing volatile pollutants from sewage sludge-amended soil in a forest.	Human breathing volatile pollutants from sewage sludge-amended soil on a reclamation site.	Human breathing volatile pollutants from sewage sludge-amended soil on a public contact site.
14. Sewage Sludge → Soil → Ground Water → Human	Human drinking water from wells that contain pollutants leached from sewage sludge-amended agricultural land to ground water.	Human drinking water from wells that contain pollutants leached from sewage sludge-amended soil in a forest to ground water.	Human drinking water from wells that contain pollutants leached from sewage sludge-amended soil on a reclamation site to ground water.	Human drinking water from wells that contain pollutants leached from sewage sludge-amended soil on a public contact site to ground water.
15. Exposure to mother from pathways 1, 2, 4, 5, 12, 13, and 14 → Nursing Infant	Nursing infant of exposed mother.	Nursing infant of exposed mother.	Nursing infant of exposed mother.	Nursing infant of exposed mother.

NA - Not Applicable

EXHIBIT 4-3
Average Values for Sewage Sludge Land Application Parameters

Parameter	Definition	Value	Notes
N, agricultural land	Number of years of application to agricultural land	20	assumed applied once every year for 20 year site life (U.S. EPA, 1993a)
N, forest	Number of years of application to forest land	7	assumed applied once every three years for 20 year site life (U.S. EPA, 1984)
N, reclamation sites	Number of years of application to reclamation sites	1	assumed one-time application
N, public contact	Number of years of application to public contact sites	10	assumed applied once every two years for 20 year site life (U.S. EPA, 1984)
N_{site}, agricultural land, forest, public contact	Site life, i.e., period of time during which sewage sludge may be applied	20yr	
N_{site}, reclamation site	Site life, i.e., period of time during which sewage sludge may be applied	1yr	
d, agricultural land	Depth of incorporation on agricultural land	15 cm	U.S. EPA, 1992a
d, forest	Depth of incorporation on forest land	0 cm	no incorporation assumed
d, reclamation sites	Depth of incorporation on reclamation sites	10 cm	U.S. EPA, 1984
d, public contact	Depth of incorporation on public contact sites	0 cm	no incorporation assumed
AR, agricultural land	Annual whole sludge application rate for agricultural land	7 dry Mg/ha-yr[1]	U.S. EPA, 1992a
AR, forest	Annual whole sludge application rate for forest land	26 dry Mg/ha-yr[1]	U.S. EPA, 1992a
AR, reclamation sites	Annual whole sludge application rate for reclamation sites	74 dry Mg/ha-yr[1]	U.S. EPA, 1992a
AR, public contact	Annual whole sludge application rate for public contact sites	18 dry Mg/ha-yr[1]	U.S. EPA, 1992a
BD_{soil}	Bulk density of soil at agricultural land and reclamation sites	1600 kg/m^3	U.S. EPA, 1992a
BD_{mix}	Bulk density of sewage sludge-amended soil	1400 kg/m^3	U.S. EPA, 1992a

[1] Note that 1 Mg = 1 megagram = 1 metric ton = 1000 kg.

EXHIBIT 4-4
Background Concentrations of Pollutants in Soil

Pollutant	90th Percentile Background Concentration in Soil[1] (mg/kg dry weight)	Ratio of Sewage Sludge (95th) to Soil Concentrations (dimensionless)
Aluminum	68,000	0.54
Antimony	0.51	47
Barium	452	3.8
Beryllium	0.65	12
Boron	27	6.7
Cyanide (soluble salts and complexes)	NA	NA
Fluoride	220	1.9
Manganese	342	4.7
Silver	0[2]	NA
Thallium	0[3]	NA
Tin	0.94	150
Titanium	3400	0.11
Vanadium	60	1.1

NA means Not Available.
[1] Concentration obtained by calculating 90th percentile value, based on geometric means and standard deviations obtained from U.S. Geological Survey, 1992.
[2] Silver was measured too infrequently for a reliable mean concentration to be calculated, as discussed in U.S. Geological Survey, 1992.
[3] Thallium was analyzed for in all samples but was never found, as discussed in U.S. Geological Survey, 1992.

4.2.1 Pathway 1 - Ingestion of Crops Grown on Sewage Sludge-Amended Soil

Pathway 1 evaluates human ingestion of plants that have taken up pollutants from sewage sludge-amended agricultural and non-agricultural lands. Non-agricultural lands include forests, reclaimed land, and public contact sites.

Mass Balance Equations

To be conservative in these analyses, the entire mass of a pollutant applied in sewage sludge over the life of a land application site is assumed to be available for plant uptake. Unlike Pathway 1 in the Technical Support Document for Land Application of Sewage Sludge, developed for the Round One regulation (U.S. EPA, 1992a), this analysis does not assume that organic pollutants either degrade or volatilize each year between sewage sludge applications. This conservative approach is used for this level of assessment because: (a) plant uptake of most pollutants is low and (b) the dissipation of many of the pollutants being considered in Round Two is slow. If this pathway yielded high risk for a particular pollutant, the assumptions would be refined.

In calculating total pollutant concentration in the soil (CT_j) for the agricultural and reclaimed land scenarios, the following equation is used for both inorganic and organic pollutants:

$$CT_j = \frac{(BS_j \cdot MS) + (N \cdot C_j \cdot AR)}{(N \cdot AR) + MS} \tag{4-1}$$

where:

CT_j	=	concentration of pollutant j in sewage sludge-amended soil (mg pollutant/kg sewage sludge-amended soil),
BS_j	=	background concentration (dry weight) of pollutant j in soil (mg pollutant/kg soil),
MS	=	mass of soil in mixing zone of one hectare of land (Mg soil/ha land),
N	=	total number of years sewage sludge is applied to land (yr),
C_j	=	concentration of pollutant j in sewage sludge (mg pollutant/kg sewage sludge), and
AR	=	annual whole sludge application rate of sewage sludge to land (dry Mg sewage sludge/ha-yr).

The mass of soil in the mixing zone of one hectare of land is calculated as:

$$MS = BD_{soil} \cdot d \cdot 10^{-1} \tag{4-2}$$

where:

BD_{soil}	=	bulk density of soil (kg soil/m^3 soil),
d	=	depth of incorporation (cm), and
10^{-1}	=	constant to convert (kg $\cdot$ cm/m^3) to (Mg/ha).

For forests and public contact sites, it is assumed that there is no incorporation of land-applied sewage sludge. Therefore, the concentration of each pollutant in the "soil" is set equal to its concentration in the sewage sludge.

The concentrations of pollutants in crops grown on sewage sludge-amended soil are calculated as:

$$CD_{ij} = CT_j \cdot UC_{ij} \tag{4-3}$$

where:

CD_{ij}	=	tissue concentration (dry weight) of pollutant j in crop i (mg pollutant/kg crop tissue), and
UC_{ij}	=	rate of uptake of pollutant j into tissue of crop i (μg pollutant/g dry weight crop tissue per μg pollutant/g sewage sludge-amended soil).

Exposure Equation

Once the various concentrations of a pollutant in crop tissues are estimated, they are combined with data on the fraction of crops grown on sewage sludge-amended soil and the daily dietary consumption of crops to estimate human exposure:

$$\begin{aligned} EXP_j &= \frac{10^{-3}}{BW} \sum_i CD_{ij}\, FC_i\, DC_i \\ &= \frac{10^{-3}\, CT_j}{BW} \sum_i UC_{ij}\, FC_i\, DC_i \end{aligned} \tag{4-4}$$

where:

EXP_j	=	exposure to pollutant j from crops produced on sewage sludge-amended soil (mg pollutant/kg body weight-day),
10^{-3}	=	constant to convert units from (g) to (kg),
BW	=	body weight (kg), assumed to be 70 kg,
FC_i	=	fraction of dietary consumption of crop i grown in sewage sludge-amended soil (dimensionless), and
DC_i	=	daily dietary consumption of crop i (g crop tissue/day).

Data Inputs

There are three types of data inputs specific to this pathway: daily dietary consumption of various crops, fraction of consumption derived from sewage sludge-amended soil, and pollutant-specific plant uptake rates. Values for the daily dietary consumption of crops and the fraction of consumption derived from sewage sludge-amended soil are presented in Exhibit 4-5.

EXHIBIT 4-5
Dietary Assumptions for Pathway 1

Crop	Daily Dietary Consumption of Crop (g dry weight/day)[1]	Fraction of Consumption Derived from Sewage Sludge-Amended Soil[2]
Garden Fruits	4.15	0.025
Grains and Cereals	90.7	0.025
Leafy Vegetables	1.97	0.025
Legumes	8.75	0.025
Peanuts	2.25	0.025
Potatoes	15.6	0.025
Root Vegetables	1.6	0.025
Berries	2.60	0.25[4]
Mushrooms	0.6[3]	0.25[4]

[1] Values represent the estimated lifetime average daily food intakes for the crops, in dry weight, unless otherwise noted. U.S. EPA, 1992a.
[2] Fractions represent reasonable estimates, unless otherwise noted. U.S. EPA, 1992a.
[3] Due to the potential to gather large quantities of mushrooms from forest lands, a daily dietary consumption value for a Highly Exposed Individual, not an average individual, was used. U.S. EPA, 1992a.
[4] Fractions represent reasonable worst-case assumptions. U.S. EPA, 1992a.

Plant uptake slopes are needed for the seven agricultural crop categories that represent major human dietary intakes: garden fruits (e.g., tomatoes); grains and cereals (e.g., barley, wheat); leafy vegetables (e.g., swiss chard, cabbage, lettuce); dry and fresh legumes (e.g., beans, peas); peanuts; potatoes; and, root vegetables (e.g., carrots, beets) (U.S. EPA, 1992a). In addition, plant uptake rates for berries and mushrooms are needed for non-agricultural lands. Data on plant uptake slopes, however, did not exist for all pollutant candidates and for all crops. When no data were available for a particular crop, the following extrapolations were made between crops for a given pollutant:

- grain and cereal uptake slopes and forage/pasture uptake slopes (used in animal exposure pathways) were considered interchangeable;

- potato uptake slopes and root vegetable uptake slopes were considered interchangeable;

- peanut uptake slopes and legume uptake slopes were considered interchangeable; and

- any vegetative or leafy growth uptake slopes identified in a study (e.g., soybean leaves) were used for leafy vegetable uptake slopes if no leafy vegetable studies could be identified.

When multiple data points were available for a particular pollutant and crop from a variety of studies, the average of the data from the most appropriate studies was used. The appropriateness of a given study was determined from the study hierarchy established in Round One: data from sludge-amended field studies were preferred over data from sludge-amended pot studies, which in turn were preferred over data from metal-salt-amended field or pot studies. If uptake slope data existed for a particular pollutant in a particular crop category from more than one study of the same hierarchical level, they were averaged.

For the agricultural pathway, if uptake slope data were not available or could not be estimated using the above extrapolations for all seven crops for a particular pollutant, then exposure to that pollutant was not estimated. Available plant uptake slopes for agricultural land crops are presented in Exhibit 4-6. Note that only 14 pollutant candidates had available data on plant uptake slopes for at least one crop; only three pollutant candidates had uptake slope data available for all seven crops. Therefore only three pollutants could be evaluated for this exposure pathway.

The non-agricultural Pathway 1 models human consumption of plants grown in forests, on reclaimed lands, or on public contact sites that have been amended with sewage sludge. Humans are assumed to be potentially exposed to wild berries or mushrooms. For this pathway, garden fruits were used as a surrogate for berries if actual data did not exist for organic and inorganic pollutant uptake. For uptake of organic and inorganic pollutants into mushrooms, data were not available. In the Technical Support Document for Land Application of Sewage Sludge (U.S. EPA, 1992a), it was noted that mushrooms have potential to bioaccumulate both mercury and cadmium. As shown in Exhibit 4-7, information is not available on whether mushrooms can bioaccumulate any of the Round Two pollutant candidates. Note that only four pollutant candidates, those with available wild berry uptake data, are included in the exhibit. No pollutants could be evaluated for the non-agricultural pathway due to the lack of uptake data for mushrooms.

EXHIBIT 4-6
Available Plant Uptake Slopes for Agricultural Pathway 1

Pollutant	Plant Uptake Slopes (µg/g crop tissue per µg/g soil)						
	Garden Fruits	Grains and Cereals	Leafy Vegetables	Fresh and Dry Legumes	Peanuts	Potatoes	Root Vegetables
Aluminum		3.13[1]	0.0026[2]				
Antimony			0.103[3]				
Barium			0.0695[4]				
Beryllium		0.31[5]	12.2[6]			0.49[7]	0.49[7]
Boron	2.29[8]	3.9[9]	3.115[10]	109.075[11]	109.075[11]		
Dioxins and Dibenzofurans	0.000036[12]	0.0043[13,14]	0.009[13]	0.0043[13]	0.0043[13]	0.00145[12]	0.00145[12]
Fluoride	0.35[15]	0.4367[16]	1.875[17]	2.24[18]	2.24[18]	0.2475[19]	0.2475[19]
Manganese		9.98[20]	1.5565[21]			8.4[22]	8.4[22]
Polychlorinated biphenyls (coplanar)		2[23]					
Silver		0.021[24]					
Thallium			22.47[25]	18.73[26]	18.73[26]		
Tin			0.3352[27]				
Titanium	0.136[28]	0.0325[29]	0.028[30]	0.7288[31]	1.22[31]	0.13[32]	0.13[32]
Vanadium			0.0062[33]				

Key to Study Type:
A: Based on sewage sludge field study.
B: Based on non-field sewage sludge study.
C: Based on non-sewage sludge study.

Footnotes:
[1] Muchovej et al., 1986 (ryegrass: 3.13): C.
[2] Chaney et al., 1978 (swiss chard: 0.00301): A; Babish et al., 1979 (cabbage: 0.0021): A.
[3] Chaney et al., 1978 (swiss chard: 0.194): A; Babish et al., 1979 (cabbage: 0.012): A.
[4] Chaney et al., 1978 (swiss chard: 0.097): A; Babish, et al., 1979 (cabbage: 0.042): A.
[5] Bohn and Seekamp, 1979 (oats: 0.31): C.
[6] Kosak-Channing, 1986 (tobacco leaves: 12.2): C.
[7] Bohn and Seekamp, 1979 (potatoes: 0.49): C.
[8] Soon and Bates, 1985 (corn kernels: 2.29): A.
[9] Soon and Bates, 1985 (bromegrass: 3.9): A.
[10] Chaney et al., 1978 (swiss chard: 3.43): A; Babish et al., 1979 (cabbage: 2.8): A.
[11] Agbenin et al., 1991 (cowpea: 134.4): C; Stark and Redente, 1990 (alfalfa: 83.75): C.
[12] U.S. EPA, 1992d. Estimated from model. Assumed dry weight basis.
[13] U.S. EPA, 1994a. Fresh weight basis.
[14] Assumed to be the same as legumes.
[15] Doss et al., 1977 (tomatoes: 0.35): C.
[16] Davis, 1980 (first cut rye: 0.18); Singh et al., 1979b (wheat: 0.8): C; Singh et al., 1979a (rice: 0.33): C.
[17] Bar-Yosef and Rosenberg, 1988 (corn shoot: 3.4, tomato shoot: 3.8): C; Doss et al., 1977 (lettuce: 0.5, petunia leaves: 1.0, potato leaves: 0.675): C.
[18] Stark and Redente, 1990 (alfalfa: 2.24): C.
[19] Doss et al., 1977 (potato: 0.2475): C.
[20] Kalbasi, 1988 (sorghum: 9.98): C.
[21] Chaney et al., 1978 (swiss chard: 3.09): A; Babish et al., 1979 (cabbage: 0.023): A.
[22] Denduluri, 1993 (okra roots: 8.4): C.
[23] Webber et al., 1983 (whole oat: 2.0): A.
[24] Romney et al., 1977 (barley: 0.021): C.
[25] Kaplan et al., 1990 (bean leaves: 22.47): C.
[26] Kaplan et al., 1990 (bean pods: 18.73): C.
[27] Chaney et al., 1978 (swiss chard: 0.6604): A; Babish et al., 1979 (cabbage: 0.01): A.
[28] Tonkonozhenko and Khlyupina, 1974 (corn kernels: 0.136): C.
[29] Tonkonozhenko and Khlyupina, 1974 (winter wheat grains: 0.035, rice grains: 0.03): C.
[30] Babish et al., 1979 (cabbage: 0.028): A.
[31] Tonkonozhenko and Khlyupina, 1974 (peas: 0.2375, beans: 1.22): C.
[32] Tonkonozhenko and Khlyupina, 1974 (sugar beets: 0.13): C.
[33] Chaney et al., 1978 (swiss chard: 0.00645): A; Babish et al., 1979 (cabbage: 0.006): A.

EXHIBIT 4-7
Available Plant Uptake Slopes for Non-Agricultural Pathway 1

Pollutant	Plant Uptake Slopes ($\mu g/g$ crop tissue per $\mu g/g$ soil)	
	Berries	Mushrooms
Boron	2.29[1]	
Dioxins and Dibenzofurans	0.000036[2]	
Fluoride	0.35[3]	
Titanium	0.136[4]	

Key to Study Type:
A: Studies conducted in the field with sewage sludge.
B: All other studies conducted with sewage sludge.
C: All other studies.

Footnotes:
[1] Soon and Bates, 1985 (corn kernels: 2.29): A.
[2] U.S. EPA, 1992b. Estimated from model. Assumed dry weight basis.
[3] Doss et al., 1977 (tomatoes: 0.35): C.
[4] Tonkonozhenko and Khlyupina, 1974 (corn kernels: 0.136): C.

Example Exposure Calculation for Pathway 1

The following example presents the calculations for estimating human exposure to fluoride in sewage sludge applied to agricultural land. Fluoride is one of three pollutants with plant uptake slopes for all seven crops. The example uses the equations and input data presented above for Pathway 1.

First, the mass of soil in the mixing zone, *MS*, is estimated for agricultural land by using Eq. 4-2:

$$MS = \frac{1600kg}{m^3} \cdot 15cm \cdot \frac{10^{-1}Mg/ha}{kg \cdot cm/m^3} = \frac{2400Mg}{ha}$$

where:

1600	=	BD_{soil} (bulk density of soil) from Exhibit 4-3,
15	=	*d* (depth of incorporation for agricultural land) from Exhibit 4-3, and
10^{-1}	=	constant to convert ($kg \cdot cm/m^3$) to (Mg/ha).

Then, the concentration of fluoride in agricultural soil is calculated using Eq. 4-1:

$$CT_{fluoride} = \frac{\left(\frac{220mg}{kg} \cdot \frac{2400Mg}{ha}\right) + \left(20yr \cdot \frac{411mg}{kg} \cdot \frac{7Mg}{ha\text{-}yr}\right)}{\left(20yr \cdot \frac{7Mg}{ha\text{-}yr}\right) + \frac{2400Mg}{ha}}$$

$$= 230 mg/kg$$

where:

220	=	BS_j (background concentration of fluoride in soil) from Exhibit 4-4,
2400	=	MS (mass of soil in agricultural mixing zone), estimated above,
20	=	N (total number of years sewage sludge is applied to agricultural land) from Exhibit 4-3,
411	=	C_j (fluoride concentration in sewage sludge) from Exhibit 4-1, and
7	=	AR (application rate of sewage sludge to agricultural land) from Exhibit 4-3.

Total dietary exposure is then determined using Eq. 4-4:

$$EXP_{fluoride} = \left[\frac{10^{-3}\ kg/g \cdot 230\ mg/kg}{70\ kg}\right] \cdot [(0.35g/g \cdot 0.025 \cdot 4.15g/day)$$
$$+ (0.44g/g \cdot 0.025 \cdot 90.7g/day) + (1.9g/g \cdot 0.025 \cdot 1.97g/day)$$
$$+ (2.2g/g \cdot 0.025 \cdot 8.75g/day) + (2.2g/g \cdot 0.025 \cdot 2.25g/day)$$
$$+ (0.25g/g \cdot 0.025 \cdot 15.6g/day) + (0.25g/g \cdot 0.025 \cdot 1.6g/day)]$$
$$= 0.0061 mg/kg\text{-}day$$

where:

10^{-3}	=	constant to convert units from (g) to (kg),
230	=	CT_j (concentration of fluoride in agricultural soil), estimated above,
70	=	BW (body weight), assumed to be 70 kg,
$0.35 \cdot 0.025 \cdot 4.15$	=	contribution to dietary exposure from garden fruits,
$0.44 \cdot 0.025 \cdot 90.7$	=	contribution to dietary exposure from grains and cereals,
$1.9 \cdot 0.025 \cdot 1.97$	=	contribution to dietary exposure from leafy vegetables,
$2.2 \cdot 0.025 \cdot 8.75$	=	contribution to dietary exposure from legumes,
$2.2 \cdot 0.025 \cdot 2.25$	=	contribution to dietary exposure from peanuts,
$0.25 \cdot 0.025 \cdot 15.6$	=	contribution to dietary exposure from potatoes, and
$0.25 \cdot 0.025 \cdot 1.6$	=	contribution to dietary exposure from root vegetables.

Contribution to dietary exposure is derived as the product of UC_{ij} (uptake slope of fluoride into crop) from Exhibit 4-6, FC_i (fraction of dietary consumption of crop grown in sewage sludge-amended soil) from Exhibit 4-5, and DC_i (daily dietary consumption of crop) from Exhibit 4-5.

4.2.2 Pathway 2 - Ingestion of Crops Grown in Sewage Sludge-Amended Home Gardens

Pathway 2 evaluates human ingestion of plants that have taken up pollutants from sewage sludge-amended home gardens. The mass balance and exposure equations used are identical to those for Pathway 1 (Section 4.2.1).

Data Inputs

There are three types of data inputs specific to this pathway: the daily dietary consumption of specific crops, the fraction of that daily consumption that comes from sewage sludge-amended home gardens, and pollutant-specific plant uptake slopes. Values for the daily dietary consumption of crops and the fraction of consumption derived from sewage sludge-amended soil are presented in Exhibit 4-8.

EXHIBIT 4-8
Dietary Assumptions for Pathway 2

Crop	Daily Dietary Consumption of Crop (g/day)[1]	Fraction of Consumption Derived from Sewage Sludge-Amended Soil[2]
Garden Fruits	4.15	0.58
Grains and Cereals	89.1	0.0043
Leafy Vegetables	1.97	0.58
Fresh Legumes	3.22	0.58
Potatoes	15.6	0.37
Root Vegetables	1.60	0.58
Sweet Corn	1.60	0.58

[1] Values represent the estimated lifetime average daily food intakes for the crops. U.S. EPA, 1992a.
[2] Values are for a Highly Exposed Individual. U.S. EPA, 1992a.

Plant uptake slopes are needed for the seven crops that represent major human dietary intakes and are commonly grown by home gardeners: garden fruits (e.g., tomatoes); grains and cereals (e.g., barley, wheat); leafy vegetables (e.g., swiss chard, cabbage, lettuce); fresh legumes (e.g., beans, peas); potatoes; root vegetables (e.g., carrots, beets), and sweet corn (U.S. EPA, 1992a). Note that there are three differences between these crops and the agricultural crops used to evaluate exposure in Pathway 1. First, only fresh legumes are considered for Pathway 2, not both fresh and dry, because home gardeners do not usually grow the dried legumes they consume. Second, peanuts are not considered in Pathway 2, also because home gardeners do not usually grow the peanuts they consume. Third, sweet corn is separated out as a food group for home gardeners because so many gardeners grow sweet corn. In Pathway 1, sweet corn is included in the category of cereals and grains. In Pathway 2, the percent of sweet corn that is homegrown differs from the percent of grains and cereals that are homegrown, and thus the two food categories are separated. The non-agricultural crops of Pathway 1, berries and mushrooms, which are grown on forest land, reclaimed sites, and public contact sites, are not considered relevant for home gardens.

Data on plant uptake slopes did not exist for all pollutant candidates and for all crops. When no data were available for a particular crop, the following extrapolations were made between crops for a given pollutant:

- grain and cereal uptake slopes and forage/pasture uptake slopes (used in animal exposure pathways) were considered interchangeable;

- potato uptake slopes and root vegetable uptake slopes were considered interchangeable;

- peanut uptake slopes and legume uptake slopes were considered interchangeable; and

- any vegetative or leafy growth uptake slopes identified in a study (e.g., soybean leaves) were used for leafy vegetable uptake slopes if no leafy vegetable studies could be identified.

When multiple data points were available for a particular pollutant and crop from a variety of studies, the average of the data from the most appropriate studies was used. The appropriateness of a given study was determined from the study hierarchy established in Round One: data from sludge-amended field studies were preferred over data from sludge-amended pot studies, which in turn were preferred over data from metal-salt-amended field or pot studies. If uptake slope data existed for a particular pollutant in a particular crop from more than one study of the same hierarchical level, they were averaged.

Even after all of the above extrapolations were made, many pollutants still had data gaps. If uptake slope data were not available or could not be estimated using the above extrapolations for all seven crops for a particular pollutant, then exposure to that pollutant was not estimated. Available plant uptake slopes are presented in Exhibit 4-9. Note that the exhibit includes only the 14 pollutant candidates for which there were uptake data for at least one crop. Only three pollutant candidates could be evaluated for this exposure pathway because only three pollutant candidates had uptake slope data available for all seven crops.

EXHIBIT 4-9
Available Plant Uptake Slopes for Agricultural Pathway 2

Pollutant	Plant Uptake Slopes (μg/g crop tissue per μg/g soil)						
	Garden Fruits	Grains and Cereals	Leafy Vegetables	Fresh Legumes	Potatoes	Root Vegetables	Sweet Corn
Aluminum		3.13[1]	0.0026[2]				
Antimony			0.103[3]				
Barium			0.0695[4]				
Beryllium		0.31[5]	12.2[6]		0.49[7]	0.49[7]	
Boron	2.29[8]	3.9[9]	3.115[10]	109.075[11]			2.29[8]
Dioxins and Dibenzofurans	0.000036[12]	0.0043[13,14]	0.009[13]	0.0043[13]	0.00145[12]	0.00145[12]	0.000036[12]
Fluoride	0.35[15]	0.4367[16]	1.875[17]	2.24[18]	0.2475[19]	0.2475[19]	0.35[15]
Manganese		9.98[20]	1.5565[21]		8.4[22]	8.4[22]	
Polychlorinated biphenyls (coplanar)		2[23]					
Silver		0.021[24]					
Thallium			22.47[25]	18.73[26]			
Tin			0.3352[27]				
Titanium	0.136[28]	0.0325[29]	0.028[30]	0.7288[31]	0.13[32]	0.13[32]	0.136[28]
Vanadium			0.0062[33]				

Key to Study Type:
A: Based on sewage sludge field study.
B: Based on non-field sewage sludge study.
C: Based on non-sewage sludge study.

Footnotes:
[1] Muchovej et al., 1986 (ryegrass: 3.13): C.
[2] Chaney et al., 1978 (swiss chard: 0.00301): A; Babish et al., 1979 (cabbage: 0.0021): A.
[3] Chaney et al., 1978 (swiss chard: 0.194): A; Babish et al., 1979 (cabbage: 0.012): A.
[4] Chaney et al., 1978 (swiss chard: 0.097): A; Babish, et al., 1979 (cabbage: 0.042): A.
[5] Bohn and Seekamp, 1979 (oats: 0.31): C.
[6] Kosak-Channing, 1986 (tobacco leaves: 12.2): C.
[7] Bohn and Seekamp, 1979 (potatoes: 0.49): C.
[8] Soon and Bates, 1985 (corn kernels: 2.29): A.
[9] Soon and Bates, 1985 (bromegrass: 3.9): A.
[10] Chaney et al., 1978 (swiss chard: 3.43): A; Babish et al., 1979 (cabbage: 2.8): A.
[11] Agbenin et al., 1991 (cowpea: 134.4): C; Stark and Redente, 1990 (alfalfa: 83.75): C.
[12] U.S. EPA, 1992d. Estimated from model. Assumed dry weight basis.
[13] U.S. EPA, 1994a. Fresh weight basis.
[14] Assumed to be the same as legumes.
[15] Doss et al., 1977 (tomatoes: 0.35): C.
[16] Davis, 1980 (first cut rye: 0.18); Singh et al., 1979b (wheat: 0.8): C; Singh et al., 1979a (rice: 0.33): C.
[17] Bar-Yosef and Rosenberg, 1988 (corn shoot: 3.4, tomato shoot: 3.8): C; Doss et al., 1977 (lettuce: 0.5, petunia leaves: 1.0, potato leaves: 0.675): C.
[18] Stark and Redente, 1990 (alfalfa: 2.24): C.
[19] Doss et al., 1977 (potato: 0.2475): C.
[20] Kalbasi, 1988 (sorghum: 9.98): C.
[21] Chaney et al., 1978 (swiss chard: 3.09): A; Babish et al., 1979 (cabbage: 0.023): A.
[22] Denduluri, 1993 (okra roots: 8.4): C.
[23] Webber et al., 1983 (whole oat: 2.0): A.
[24] Romney et al., 1977 (barley: 0.021): C.
[25] Kaplan et al., 1990 (bean leaves: 22.47): C.
[26] Kaplan et al., 1990 (bean pods: 18.73): C.
[27] Chaney et al., 1978 (swiss chard: 0.6604): A; Babish et al., 1979 (cabbage: 0.01): A.
[28] Tonkonozhenko and Khlyupina, 1974 (corn kernels: 0.136): C.
[29] Tonkonozhenko and Khlyupina, 1974 (winter wheat grains: 0.035, rice grains: 0.03): C.
[30] Babish et al., 1979 (cabbage: 0.028): A.
[31] Tonkonozhenko and Khlyupina, 1974 (peas: 0.2375, beans: 1.22): C.
[32] Tonkonozhenko and Khlyupina, 1974 (sugar beets: 0.13): C.
[33] Chaney et al., 1978 (swiss chard: 0.00645): A; Babish et al., 1979 (cabbage: 0.006): A.

Example Exposure Calculation for Pathway 2

The following example presents the calculations for estimating human exposure to fluoride in sewage sludge applied to a home garden. The example uses the equations and input data presented above for Pathway 2.

First, the mass of soil in the mixing zone, *MS*, is estimated for a home garden by using Eq. 4-2:

$$MS = \frac{1600kg}{m^3} \cdot 15cm \cdot \frac{10^{-1}Mg/ha}{kg \cdot cm/m^3} = \frac{2400Mg}{ha}$$

where:

1600	=	BD_{soil} (bulk density of soil) from Exhibit 4-3,
15	=	*d* (depth of incorporation for agricultural land) from Exhibit 4-3, and
10^{-1}	=	constant to convert (kg · cm/m^3) to (Mg/ha).

Then, the concentration of fluoride in soil is calculated using Eq. 4-1:

$$CT_{fluoride} = \frac{\left(\frac{220mg}{kg} \cdot \frac{2400Mg}{ha}\right) + \left(20yr \cdot \frac{411mg}{kg} \cdot \frac{7Mg}{ha-yr}\right)}{\left(20yr \cdot \frac{7Mg}{ha-yr}\right) + \frac{2400Mg}{ha}}$$

$$= 230mg/kg$$

where:

220	=	BS_j (background concentration of fluoride in soil) from Exhibit 4-4,
2400	=	*MS* (mass of soil in home garden mixing zone), estimated above,
20	=	*N* (total number of years sewage sludge is applied to home garden) from Exhibit 4-3,
411	=	C_j (fluoride concentration in sewage sludge) from Exhibit 4-1, and
7	=	*AR* (application rate of sewage sludge to home garden) from Exhibit 4-3.

Total dietary exposure is then determined using Eq. 4-4:

$$EXP_{fluoride} = [\frac{10^{-3}\ kg/g \cdot 230\ mg/kg}{70\ kg}] \cdot [(0.35 g/g \cdot 0.58 \cdot 4.15 g/day)$$
$$+ (0.44 g/g \cdot 0.0043 \cdot 89.1 g/day) + (1.9 g/g \cdot 0.58 \cdot 1.97 g/day)$$
$$+ (2.2 g/g \cdot 0.58 \cdot 3.22 g/day) + (0.25 g/g \cdot 0.37 \cdot 15.6 g/day)$$
$$+ (0.25 g/g \cdot 0.58 \cdot 1.6 g/day) + (0.35 g/g \cdot 0.58 \cdot 1.6 g/day)]$$
$$= 0.031 mg/kg\text{-}day$$

where:

10^{-3}	=	constant to convert units from (g) to (kg),
230	=	CT_j (concentration of fluoride in agricultural soil), estimated above,
70	=	*BW* (body weight), assumed to be 70 kg,
$0.35 \cdot 0.58 \cdot 4.15$	=	contribution to dietary exposure from garden fruits,
$0.44 \cdot 0.0043 \cdot 89.1$	=	contribution to dietary exposure from grains and cereals,
$1.9 \cdot 0.58 \cdot 1.97$	=	contribution to dietary exposure from leafy vegetables,
$2.2 \cdot 0.58 \cdot 3.22$	=	contribution to dietary exposure from fresh legumes,
$0.25 \cdot 0.37 \cdot 15.6$	=	contribution to dietary exposure from potatoes,
$0.25 \cdot 0.58 \cdot 1.6$	=	contribution to dietary exposure from root vegetables, and
$0.35 \cdot 0.58 \cdot 1.6$	=	contribution to dietary exposure from sweet corn.

Contribution to dietary exposure is derived as the product of UC_{ij} (uptake slope of fluoride into crop) from Exhibit 4-9, FC_i (fraction of dietary consumption of crop grown in sewage sludge-amended soil) from Exhibit 4-8, and DC_i (daily dietary consumption of crop) from Exhibit 4-8.

4.2.3 Pathway 3 - Direct Ingestion of Sewage Sludge by Children

Pathway 3 evaluates children's exposure to pollutants from direct ingestion of sewage sludge applied to land. The agricultural and non-agricultural scenarios are different in their assumptions regarding the age of children who ingest sewage sludge. At agricultural and public contact sites, children ages 1 to 6 are assumed to be exposed, whereas for forest and reclaimed sites, only older children ages 4 to 6 are assumed to have the opportunity for exposure. For all scenarios, children are assumed to be exposed directly to sewage sludge from storage piles or from the soil surface, not to a sewage sludge/soil mixture.

Data Inputs and Exposure Equation

As in Round One, children (ages 1 to 6) exposed to agricultural land and public contact sites are assumed to ingest 0.2 g soil (dry weight) per day, and weigh 16 kg. Older children (ages 4 to 6) exposed to forest and reclaimed sites are assumed to ingest 0.2 g soil per day, and weigh 19 kg. The ingestion rate of 0.2 g soil per day is a high-end value, but does <u>not</u> represent a PICA child. The body weights are average values. Exposure is calculated as:

$$EXP_j = \frac{I_s \cdot 10^{-3} \cdot C_j}{BW} \tag{4-5}$$

where:

EXP_j	=	exposure to pollutant j in sewage sludge (mg pollutant/kg body weight-day),
IS	=	sewage sludge ingestion rate (g sewage sludge/day),
10^{-3}	=	constant to convert units from (g/day) to (kg/day),
C_j	=	concentration of pollutant j in sewage sludge (mg pollutant/kg sewage sludge), and
BW	=	body weight (kg).

Example Exposure Calculation for Pathway 3

The exposure of a child to fluoride from directly ingesting sewage sludge applied to agricultural land can be estimated from Eq. 4-5:

$$EXP_{fluoride} = \frac{\frac{0.2g}{day} \cdot \frac{10^{-3}kg}{g} \cdot \frac{411mg}{kg}}{16kg}$$

$$= 0.0051 \; mg/kg\text{-}day$$

where:

0.2	=	IS (sewage sludge ingestion rate for agricultural land), from Data Inputs section above,

10^{-3}	=	constant to convert (g) to (kg),
411	=	C_j (concentration of fluoride in sewage sludge) from Exhibit 4-1, and
16	=	BW (body weight of child assumed to be exposed to agricultural land), from Methods section above.

4.2.4 Pathway 4 - Ingestion of Animal Products Produced From Animals Consuming Forage/Pasture Grown on Sewage Sludge-Amended Soil

Pathway 4 calculates human exposure to pollutants through consumption of animals that ingest forage/pasture grown on sewage sludge-amended soils. In the agricultural Pathway 4, animals ingest forage and pasture produced on sewage sludge-amended soil. Humans then ingest animal products, such as beef, pork, lamb, poultry, dairy products, and eggs. The non-agricultural Pathway 4 examines human exposure to pollutants through consumption of deer and elk that forage on sewage sludge-amended forest land and reclaimed land.

Methods

As in Pathways 1 and 2, to be conservative, the entire mass of pollutant applied in sewage sludge over the life of a land application site is assumed to be available for plant uptake (see Section 4.2.1). In calculating total pollutant concentration in the soil for the agricultural and reclaimed land scenarios, Eq. 4-1 from Section 4.2.1 is used for inorganics and organics. The expected concentrations of pollutants in forage/pasture grown on sewage sludge-amended soil are then estimated using Eq. 4-3 from Section 4.2.1.

To estimate concentrations of pollutants in animal tissues, the forage/pasture pollutant concentrations are combined with animal uptake rates. In this calculation it is assumed that forage is 100 percent of the animal's diet:

$$CA_{jk} = CD_{forage,\,j} \cdot U_{jk} \tag{4-6}$$

where:

CA_{jk}	=	concentration of pollutant j in animal product k (mg pollutant/kg animal tissue),
$CD_{forage,\,j}$	=	tissue concentration (dry weight) of pollutant j in forage/pasture (mg pollutant/kg forage/pasture), and
U_{jk}	=	rate of uptake of pollutant j into animal product k (mg pollutant/ kg dry weight animal tissue per mg pollutant/kg dry weight diet).

Once the concentrations of pollutants in animal tissues have been estimated, they are combined with data on the daily dietary consumption of animal products and on the fraction of these animal products that are produced on sewage sludge-amended soil to estimate human exposure:

$$EXP_j = \frac{10^{-3}}{BW} \sum_k CA_{jk}\ FA_k\ DA_k$$

$$= \frac{10^{-3}\ CD_{forage,\,j}}{BW} \sum_k U_{jk}\ FA_k\ DA_k \qquad (4\text{-}7)$$

where:

EXP_j	=	exposure to pollutant j from animal products produced on sewage sludge-amended soil (mg pollutant/kg body weight-day),
10^{-3}	=	constant to convert units from (g) to (kg),
BW	=	body weight (kg), assumed to be 70 kg,
FA_k	=	fraction of dietary consumption of animal product k produced on sewage sludge-amended soil (dimensionless), and
DA_k	=	daily dietary consumption of animal product k (g dry weight animal product/day).

Data Inputs

This pathway requires data on pollutant uptake rates into forage/pasture and animal products as well as data on daily dietary consumption of specific animal products and the fraction of that daily consumption that comes from animals feeding on forage/pasture produced on sewage sludge-amended soil. Values used for the latter two parameters are shown in Exhibit 4-10.

EXHIBIT 4-10
Dietary Assumptions for Pathway 4

Animal Product	Daily Dietary Consumption of Animal Product (g/day)[1]	Fraction of Consumption Derived from Sewage Sludge-Amended Soil[2]
Beef (lean)	19.3	$9.7\text{x}10^{-2}$
Beef Fat	15.5	$9.7\text{x}10^{-2}$
Beef Liver (lean and fat)	1.1	$9.7\text{x}10^{-2}$
Dairy (non-fat)	28.9	$3.1\text{x}10^{-2}$
Dairy Fat	18.1	$3.1\text{x}10^{-2}$
Eggs	8.3	$7.9\text{x}10^{-2}$
Lamb (lean)	0.20	$9.7\text{x}10^{-2}$
Lamb Fat	0.21	$9.7\text{x}10^{-2}$

EXHIBIT 4-10
Dietary Assumptions for Pathway 4 (cont'd.)

Animal Product	Daily Dietary Consumption of Animal Product (g/day)[1]	Fraction of Consumption Derived from Sewage Sludge-Amended Soil[2]
Poultry (lean)	6.7	$1.1x10^{-1}$
Poultry Fat	1.3	$1.1x10^{-1}$
Pork (lean)	9.0	$9.7x10^{-2}$
Pork Fat	12.7	$9.7x10^{-2}$
Deer (lean)	15.3[3]	1
Deer Fat	5.1[3]	1
Deer Liver (total)	0.38[3]	1
Elk (lean)	30.6[3]	0.5
Elk Fat	10.2[3]	0.5
Elk Liver (total)	0.76[3]	0.5

[1] Values represent the estimated lifetime average daily food intakes for the animal products unless otherwise noted. U.S. EPA, 1992a.
[2] Fractions represent reasonable estimates. U.S. EPA, 1992a.
[3] It was assumed that total consumption of deer and elk meat and fat constitutes 50 percent of the HEI's consumption of agricultural animal products. U.S. EPA, 1992a.

If no data were available on pollutant uptake slopes into forage/pasture, it was assumed that grain and cereal uptake slopes and forage/pasture uptake slopes were interchangeable. When multiple data points were available from a variety of studies for the uptake of a particular pollutant into forage/pasture crops, the average of the data from the most appropriate studies was used. The appropriateness of a given study was determined from the study hierarchy established in Round One: data from sewage sludge-amended field studies were preferred over data from sewage sludge-amended pot studies, that in turn were preferred over data from metal-salt-amended field or pot studies. If uptake slope data existed for a particular pollutant from more than one study of the same hierarchical level, they were averaged.

Available plant uptake data are presented in Exhibit 4-11. Note that if forage/pasture uptake data were not available for a particular pollutant, that pollutant is not included in the exhibit.

EXHIBIT 4-11
Forage/Pasture Uptake Slopes for Agricultural Pathway 4

Pollutant	Forage/Pasture Uptake Slopes (μg/g plant per μg/g soil)
Aluminum	3.13[1]
Beryllium	0.31[2]
Boron	3.9[3]
Dioxins and Dibenzofurans	0.024[4]
Fluoride	0.6775[5]
Manganese	8.22[6]
Polychlorinated biphenyls (coplanar)	2.0[7]
Silver	0.021[8]
Titanium	0.0543[9]

Key to Study Type:
A: Based on sewage sludge field study.
B: Based on non-field sewage sludge study.
C: Based on non-sewage sludge study.

Footnotes:
[1] Muchovej et al., 1986 (ryegrass: 3.13): C.
[2] Bohn and Seekamp, 1979 (oats: 0.31): C.
[3] Soon and Bates, 1985 (bromegrass: 1.64): A.
[4] U.S. EPA, 1992d. Estimated from model.
[5] Stark and Redente, 1990 (grasses: 0.58): C; Singh et al., 1979b (wheat: 0.8): C; Singh et al., 1979a (rice: 0.33): C; Doss et al., 1977 (petunia leaves: 1.0): C.
[6] Denduluri, 1993 (okra stems: 11.3, okra leaves: 12.6): C; El-Kherbawy and Sanders, 1984 (clover: 0.76): C.
[7] Webber et al., 1983 (whole oat: 2.0): A.
[8] Romney et al., 1977 (barley: 0.021): C.
[9] Tonkonozhenko and Khlyupina, 1974 (winterwheat leaves+stem: 0.07, clover leaves+stems: 0.063, rice: 0.03): C.

Ideally, for animal uptake slopes, uptake data for each pollutant into each animal product tissue would be available. A literature search revealed information on animal uptake slopes for only four pollutants: aluminum, barium, boron, and manganese. Unfortunately, uptake data were not available for all agricultural animal products of interest. Although uptake data into beef, beef liver, lamb, pork, and non-fat dairy products were considered interchangeable with available uptake data for sheep and goats, extrapolations could not be made to poultry or eggs. For non-agricultural animal products, however, tissue values for sheep, goats, deer, and elk were considered interchangeable in the lean and liver tissue categories. Therefore, risk estimates could be made for forests and reclaimed land. For coplanar PCBs, uptake values were taken directly from Round One values for PCBs.

Exhibit 4-12 presents the available animal uptake slopes for the agricultural animal products of interest; Exhibit 4-13 presents the available uptake slopes for non-agricultural animals. As before, note that only those pollutant candidates with data for at least one animal uptake slope are included in the exhibits.

EXHIBIT 4-12
Animal Uptake Slopes for Agricultural Pathway 4

Pollutant	Animal Uptake Slopes ($\mu g/g$ animal per $\mu g/g$ feed)											
	Beef Fat	Beef Liver	Beef (Lean)	Lamb Fat	Lamb (Lean)	Pork Fat	Pork (Lean)	Poultry Fat	Poultry (Lean)	Dairy Fat	Dairy (Non-Fat)	Eggs
Aluminum	NA	0.007[1]	0.021[1]	NA	0.021[1]	NA	0.021[1]	NA		NA	0.021[1]	
Barium	NA	0.0535[3]	0.088[3]	NA	0.088[3]	NA	0.088[3]	NA		NA	0.088[3]	
Boron	NA	0.0915[1]	0.091[1]	NA	0.091[1]	NA	0.091[1]	NA		NA	0.091[1]	
Manganese	NA	0.00925[5]	0.0005[4]	NA	0.00925[5]	NA	0.00925[5]	NA		NA	0.0005[4]	
Polychlorinated biphenyls (coplanar)	4.215[2]	6.664[2]	NA	6.664[2]	NA	6.664[2]	NA	6.664[2]	NA	10.536[2]	NA	10.536[2]

NA means Not Applicable; it is assumed that inorganic pollutants are not taken up into fat, and organic pollutants are not taken up into lean.
[1] Bray et al., 1985 (goat).
[2] U.S. EPA, 1992a.
[3] Whelan, 1993 (sheep).
[4] Voigt et al., 1988 (beef).
[5] Bray et al., 1985; Voigt et al., 1988.

EXHIBIT 4-13
Animal Uptake Slopes for Non-Agricultural Pathway 4

Pollutant	Animal Uptake Slopes ($\mu g/g$ animal per $\mu g/g$ feed)					
	Deer (Lean)	Deer Fat	Deer Liver	Elk (Lean)	Elk Fat	Elk Liver
Aluminum	0.021[1]	NA	0.007[1]	0.021[1]	NA	0.007[1]
Barium	0.088[3]	NA	0.0535[3]	0.088[3]	NA	0.0535[3]
Boron	0.091[1]	NA	0.0915[1]	0.091[1]	NA	0.0915[1]
Manganese	0.00925[4]	NA	0.00925[4]	0.00925[4]	NA	0.00925[4]
Polychlorinated biphenyls (coplanar)	NA	4.215[2]	6.664[2]	NA	4.215[2]	6.664[2]

NA means Not Applicable.
[1] Bray et al., 1985 (goat).
[2] U.S. EPA, 1992a.
[3] Whelan, 1993 (sheep:muscle).
[4] Bray et al., 1985 (goat); Voigt et al., 1988 (beef).

Example Exposure Calculation for Pathway 4

The following example presents the calculations for estimating human exposure to boron from consumption of deer and elk which have eaten forage plants on forest lands amended with sewage sludge. Because it is assumed that there is no incorporation of sewage sludge into forest soils, the concentration of boron in sewage sludge is used as the relevant concentration for uptake into the forage. The concentration of boron in forage is calculated using Eq. 4-3:

$$CD_{forage,\ boron} = 182\ \frac{mg}{kg} \cdot 3.9\ \frac{\mu g/g}{\mu g/g}$$

$$= 710\ mg/kg$$

where:

182 = CT_j (concentration of boron in forest soil, equivalent to the concentration of boron in sewage sludge) from Exhibit 4-1, and

3.9 = UC_{ij} (uptake slope of boron into forage/pasture) from Exhibit 4-11.

Total dietary exposure to boron from wild animals eating plants in sewage sludge-amended forests is then determined using Eq. 4-7:

$$EXP_{boron} = [\frac{10^{-3}\ kg/g \cdot 710\ mg/kg}{70\ kg}] \cdot [(0.091 g/g \cdot 1 \cdot 15.3 g/day)$$

$$+ (0.092 g/g \cdot 1 \cdot 0.38 g/day) + (0.091 g/g \cdot 0.5 \cdot 30.6 g/day)$$

$$+ (0.092 g/g \cdot 0.5 \cdot 0.76 g/day)]$$

$$= 0.029 mg/kg\text{-}day$$

where:

10^{-3}	=	constant to convert units from (g) to (kg),
710	=	CT_j (concentration of boron in forest soil), estimated above,
70	=	BW (body weight), assumed to be 70 kg,
$0.091 \cdot 1 \cdot 15.3$	=	contribution to dietary exposure from lean deer,
$0.092 \cdot 1 \cdot 038$	=	contribution to dietary exposure from deer liver,
$0.091 \cdot 0.5 \cdot 30.6$	=	contribution to dietary exposure from lean elk, and
$0.092 \cdot 0.5 \cdot 0.76$	=	contribution to dietary exposure from elk liver.

Contribution to dietary exposure is derived as the product of UC_{jk} (uptake slope of boron into animal product) from Exhibit 4-13, FA_k (fraction of dietary consumption of animal product derived from sewage sludge-amended soil) from Exhibit 4-10, and DA_k (daily dietary consumption of animal product) from Exhibit 4-10.

4.2.5 Pathway 5 - Consumption of Animal Products Produced From Animals That Ingest Sewage Sludge

Pathway 5 involves the application of sewage sludge to land, the direct ingestion of sewage sludge by animals, and finally, the consumption of animal products by humans. Agricultural Pathway 5 considers only the direct ingestion of sewage sludge by livestock, following the surface application of sewage sludge to pasture crops. Non-agricultural Pathway 5 considers the direct ingestion of sewage sludge by livestock that graze on grasses growing on forest land or reclaimed land; the animals are then ingested by humans. The pathway does not consider the grazing of livestock on public contact sites because it is assumed such grazing would be controlled. The pathway also does not consider wild animals in forest land because deer do not graze on plants close to the ground and would not inadvertently ingest sewage sludge. Furthermore, other wild herbivorous game animals are assumed to graze over large territories.

Methods

To estimate concentrations of pollutants in animal tissues, sewage sludge pollutant concentrations are combined with percent of animal ingestion that is sewage sludge and tissue uptake rates. In this calculation the sewage sludge pollutant concentration multiplied by the animal's percentage sewage sludge consumption and pollutant uptake rate is assumed to equal the resulting animal tissue concentration of the pollutant:

$$CA_{jk} = C_j \cdot FS \cdot U_{jk} \tag{4-8}$$

where:

CA_{jk}	=	concentration of pollutant j in animal product k (mg pollutant/kg animal tissue),
C_j	=	concentration of pollutant j in sewage sludge (mg pollutant/kg sewage sludge),
FS	=	fraction of animal's diet that is sewage sludge (unitless, kg sewage sludge/kg diet), and
U_{jk}	=	rate of uptake of pollutant j into animal product k (mg pollutant/kg dry weight animal tissue per mg pollutant/kg dry weight diet).

Once the concentrations of pollutants in animal tissues have been estimated, they are combined with data on the daily dietary consumption of animal products and on the fraction of those animal products that are produced on sewage sludge-amended soil to estimate human exposure:

$$EXP_j = \frac{10^{-3}}{BW} \sum_k CA_{jk}\, FA_k\, DA_k$$

$$= \frac{10^{-3} \cdot C_j \cdot FS}{BW} \sum_k U_{jk}\, FA_k\, DA_k \tag{4-9}$$

where:

EXP_j	=	exposure to pollutant j from animal products produced on sewage sludge-amended soil (mg pollutant/kg body weight-day),
10^{-3}	=	constant to convert units from (g) to (kg),
BW	=	body weight (kg), assumed to be 70 kg,
FA_k	=	fraction of dietary consumption of animal product k produced on sewage sludge-amended soil (dimensionless), and
DA_k	=	daily dietary consumption of animal product k (g dry weight animal product/day).

Data Inputs

For this pathway, there are four data inputs required to calculate human exposure from consumption of animal products produced from animals that ingest sewage sludge: the percentage of animal diet that consists of sewage sludge, the daily dietary consumption of specific animal products, the fraction of that daily consumption which comes from animals that ingest sewage sludge, and animal uptake rates of pollutants.

The percentage of a grazing cattle's diet that is sewage sludge, averaged over a season, is estimated to be 2.5 percent (Chaney et al., 1987; Bertrand et al., 1981). However, given that in any one year, the maximum percentage of a farm treated with sewage sludge is approximately 33 percent, and assuming that livestock are rotated among several pasture fields, the actual percentage of the diet that is sewage sludge is assumed to be lower than 2.5 percent. The diet for cattle grazing on land treated with sewage sludge that was applied the previous growing season has been shown to be approximately 1.0 percent sewage sludge (Decker et al., 1980). When a weighted average is calculated from these two values of sewage sludge ingestion, the long-term average percentage of diet that is sewage sludge is 1.5 percent: ⅓(2.5%) + ⅔(1.0%) = 1.5% (Chaney et al., 1991).

Values for the daily dietary human consumption of specific animal products and the fraction of consumption from sewage sludge-amended soil are shown in Exhibit 4-14. For animal uptake slopes for beef, dairy, and lamb products, see Exhibit 4-12 in Section 4.2.4.

EXHIBIT 4-14
Dietary Assumptions for Pathway 5

Animal Product	Daily Dietary Consumption of Animal Product (g/day)[1]	Fraction of Consumption Derived from Sewage Sludge-Amended Soil[2]
Beef (Lean)	19.3	9.7×10^{-2}
Beef Fat	15.5	9.7×10^{-2}
Beef Liver	1.1	9.7×10^{-2}
Dairy (Non-Fat)	28.9	3.1×10^{-2}
Dairy Fat	18.1	3.1×10^{-2}
Lamb (Lean)	0.20	9.7×10^{-2}
Lamb Fat	0.21	9.7×10^{-2}

[1] Values represent the estimated lifetime average daily food intakes for the animal products unless otherwise noted. U.S. EPA, 1992a.
[2] Fractions represent reasonable estimates. U.S. EPA, 1992a.

Example Exposure Calculation for Pathway 5

The following example presents the calculation for estimating human exposure to manganese from consumption of livestock that ingest sewage sludge on sewage sludge-amended forest land. Using Eq. 4-9:

$$EXP_{manganese} = \left[\frac{10^{-3}\frac{kg}{g} \cdot 1620\frac{mg}{kg} \cdot 0.015}{70kg}\right] [\left(0.00925\frac{g}{g} \cdot 9.7x10^{-2} \cdot 1.1\frac{g}{day}\right) +$$

$$\left(0.0005\frac{g}{g} \cdot 9.7x10^{-2} \cdot 19.3\frac{g}{day}\right) + \left(0.00925\frac{g}{g} \cdot 9.7x10^{-2} \cdot 0.20\frac{g}{day}\right) +$$

$$\left(0.0005\frac{g}{g} \cdot 3.1x10^{-2} \cdot 28.9\frac{g}{day}\right)]$$

$$= 8.9x10^{-7}\frac{mg}{kg\text{-}day}$$

where:

10^{-3}	=	constant to convert units from (g) to (kg),
1620	=	C_j (concentration of manganese in sewage sludge) from Exhibit 4-1,
0.015	=	*FS* (fraction of animal's diet that is sewage sludge), discussed above,
70	=	*BW* (body weight), assumed to be 70 kg,
$(0.00925 \cdot 9.7 \text{ x } 10^{-2} \cdot 1.1)$	=	contribution to dietary exposure from beef liver,
$(0.0005 \cdot 9.7 \text{ x } 10^{-2} \cdot 19.3)$	=	contribution to dietary exposure from lean beef,
$(0.00925 \cdot 9.7 \text{ x } 10^{-2} \cdot 0.20)$	=	contribution to dietary exposure from lean lamb, and
$(0.0005 \cdot 3.1 \text{ x } 10^{-2} \cdot 28.9)$	=	contribution to dietary exposure from non-fat dairy.

Contribution to dietary exposure is derived as the product of U_{jk} (uptake of manganese into animal product) from Exhibit 4-12, FA_k (fraction of dietary consumption of animal product derived from sewage sludge-amended land) from Exhibit 4-14, and DA_k (daily dietary consumption of animal product) from Exhibit 4-14.

4.2.6 Pathway 6 - Animal Toxicity From Plant Consumption

Pathway 6 calculates herbivorous animal toxicity caused by the consumption of plants that are grown on sewage sludge-amended soil on both agricultural and non-agricultural lands. Non-agricultural lands include forests, reclaimed land, and public contact sites. In the agricultural pathway, the HEI is the most sensitive herbivorous livestock that consumes plants grown on sewage sludge-amended soil. For the non-agricultural forest land Pathway 6, two exposure scenarios are possible. In one, the HEI is a small herbivorous mammal that spends its entire life in a sewage sludge-amended area feeding on seeds and small plants close to the sewage sludge/soil layer. In the second scenario, the HEI is an herbivorous livestock that grazes on the grasses growing on sewage sludge-amended forest land. The HEI for reclaimed land is livestock; the HEI for public contact sites is a small herbivorous mammal.

Methods

For the agricultural Pathway 6, the animals of interest are herbivorous livestock. For the non-agricultural Pathway 6, the animals of interest are small herbivorous mammals as well as herbivorous livestock. Eq. 4-1 from Section 4.2.1 is used to calculate total pollutant concentration in the soil (CT_j) for the agricultural and reclaimed land scenarios. Exposure is reported in terms of milligrams pollutant per kilogram of diet, assuming that the herbivore receives its total diet from forage/pasture grown on sewage sludge-amended land. Therefore, the dietary exposure for the HEI can be expressed as:

$$EXPA_j = CD_j = CT_j \cdot UC_{forage,\,j} \tag{4-10}$$

where:

$EXPA_j$	=	exposure of animal to pollutant j (mg pollutant/kg diet),
CD_j	=	tissue concentration (dry weight) of pollutant j in forage/pasture (mg pollutant/kg forage/pasture),
CT_j	=	concentration of pollutant j in sewage sludge-amended soil (mg pollutant/kg sewage sludge-amended soil), and
$UC_{forage,j}$	=	rate of uptake of pollutant j into tissue of forage/pasture (mg pollutant/kg dry weight forage/pasture per mg pollutant/kg soil).

Data Inputs

For this pathway, data are needed on pollutant uptake rates into forage/pasture. For available uptake rates into forage/pasture, see Exhibit 4-11 in Section 4.2.4.

Example Exposure Calculation for Pathway 6

The following example presents the calculations for estimating exposure of herbivorous livestock to fluoride in sewage sludge applied to agricultural land.

First, the mass of soil in the mixing zone, *MS*, is estimated for agricultural land by using Eq. 4-2:

$$MS = \frac{1600kg}{m^3} \cdot 15cm \cdot \frac{10^{-1}Mg/ha}{kg \cdot cm/m^3} = \frac{2400Mg}{ha}$$

where:

1600	=	BD_{soil} (bulk density of soil) from Exhibit 4-3,
15	=	d (depth of incorporation for agricultural land) from Exhibit 4-3, and
10^{-1}	=	constant to convert (kg $\cdot$ cm/m^3) to (Mg/ha).

Then, the concentration of fluoride in agricultural soil is calculated using Eq. 4-1:

$$CT_{fluoride} = \frac{\left(\frac{220mg}{kg} \cdot \frac{2400Mg}{ha}\right) + \left(20yr \cdot \frac{411mg}{kg} \cdot \frac{7Mg}{ha\text{-}yr}\right)}{\left(20yr \cdot \frac{7Mg}{ha\text{-}yr}\right) + \frac{2400Mg}{ha}}$$

$$= 230\,mg/kg$$

where:

220	=	BS_j (background concentration of fluoride in soil) from Exhibit 4-4,
2400	=	MS (mass of soil in agricultural mixing zone), estimated above,
20	=	N (total number of years sewage sludge is applied to agricultural land) from Exhibit 4-3,
411	=	C_j (fluoride concentration in sewage sludge) from Exhibit 4-1, and
7	=	AR (application rate of sewage sludge to agricultural land) from Exhibit 4-3.

The expected exposure of livestock to fluoride in forage/pasture is calculated using Eq. 4-10:

$$EXP_{fluoride} = \frac{230mg}{kg} \cdot \frac{0.68g}{g}$$

$$= 160\ mg/kg$$

where:

230	=	CT_j (concentration of fluoride in agricultural soil), estimated above, and
0.68	=	$UC_{forage,j}$ (uptake slope of fluoride into forage/pasture) from Exhibit 4-11.

4.2.7 Pathway 7 - Animal Toxicity From Direct Ingestion of Sewage Sludge

This pathway calculates herbivorous animal toxicity caused by the direct ingestion of sewage sludge on both agricultural and non-agricultural lands. Non-agricultural lands include forests and reclaimed land. For both the agricultural and non-agricultural pathways, the HEI is the most sensitive or most exposed herbivorous livestock that directly ingests sewage sludge from sewage sludge-amended soil. This pathway does not consider exposure to sewage sludge on public contact sites because livestock usually are not grazed there.

Methods

For both the agricultural and non-agricultural Pathway 7, the HEI is herbivorous livestock. Exposure is reported in terms of milligrams pollutant per kilogram of diet, assuming that the herbivore receives its total diet from forage/pasture grown on sewage sludge-amended land. Therefore, the dietary exposure for the HEI can be expressed as:

$$EXPA_j = C_j \cdot FS \tag{4-11}$$

where:

$EXPA_j$	=	exposure of animal to pollutant j (mg pollutant/kg diet),
C_j	=	concentration of pollutant j in sewage sludge (mg pollutant/kg sewage sludge), and
FS	=	fraction of animal's diet that is sewage sludge (unitless, kg sewage sludge/kg diet).

Data Inputs

For this pathway, data are required on the percentage of animal diet that consists of sewage sludge. As described for Pathway 5, the percentage of a grazing cattle's diet that is sewage sludge, averaged over a season, is estimated to be 2.5 percent (Chaney et al., 1987; Bertrand et al., 1981). However, given that in any one year, the maximum percentage of a farm treated with sewage sludge is approximately 33 percent, and assuming that livestock are rotated among several pasture fields, the actual percentage of the diet that is sewage sludge is assumed to be lower than 2.5 percent. The diet for cattle grazing on land treated with sewage sludge that was applied the previous growing season has been shown to be approximately 1.0 percent sewage sludge (Decker et al., 1980). When a weighted average is calculated from these two values of sewage sludge ingestion, the long-term average percentage of diet that is sewage sludge is 1.5 percent: $\frac{1}{3}(2.5\%) + \frac{2}{3}(1.0\%) = 1.5\%$ (Chaney et al., 1991).

Example Exposure Calculation for Pathway 7

The exposure of herbivorous livestock to manganese from direct ingestion of sewage sludge is calculated from Eq. 4-11:

$$\begin{aligned} EXP_{manganese} &= 1620 \frac{mg}{kg} \cdot 0.015 \\ &= 24 \frac{mg}{kg} \end{aligned}$$

where:

1620	=	C_j (concentration of manganese in sewage sludge) from Exhibit 4-1, and
0.015	=	FS (fraction of animal's diet that is sewage sludge), discussed above.

4.2.8 Pathway 8 - Toxicity to Plants

This pathway could not be evaluated due to a lack of data on the phytotoxicity effects of the candidate Round Two pollutants.

4.2.9 Pathway 9 - Toxicity to Soil-Dwelling Organisms

Pathway 9 evaluates toxicity to soil-dwelling organisms due to the presence of pollutants in sewage sludge that is land-applied to agricultural and non-agricultural lands. Non-agricultural lands include forests, reclaimed land, and public contact sites. The soil-dwelling organisms considered are earthworms. There is no evidence that earthworms are the most sensitive species; however, because of a lack of data for other soil-dwelling species, earthworms are considered the HEI for this pathway.

Data Inputs and Exposure Equation

For each pollutant and type of land application site, the concentration of pollutant in the soil had to be calculated. For agricultural and reclaimed land, the pollutant concentration was calculated using Eq. 4-1 in Section 4.2.1. For forests and public contact sites, it was assumed that there would be no incorporation of land-applied sewage sludge. This implies that the soil layer to which the soil-dwelling organisms are exposed is pure sewage sludge. Therefore, the concentration of each pollutant in the exposure layer ("soil") was set equal to its concentration in the sewage sludge. For this pathway, exposure to pollutants in soil by earthworms is measured by the concentration of the pollutants in the sewage sludge/soil:

$$EXPO_j = CT_j \tag{4-12}$$

where:

$EXPO_j$ = exposure of soil-dwelling organisms to pollutant j (mg pollutant/kg sewage sludge-amended soil), and

CT_j = concentration of pollutant j in sewage sludge-amended soil (mg pollutant/kg sewage sludge-amended soil).

Example Exposure Calculation for Pathway 9

The following example estimates exposure of earthworms to manganese in agricultural soil.

For agricultural land, the mass of soil in the mixing zone, *MS*, must first be estimated by using Eq. 4-2:

$$MS = \frac{1600kg}{m^3} \cdot 15cm \cdot \frac{10^{-1}Mg/ha}{kg \cdot cm/m^3} = \frac{2400Mg}{ha}$$

where:

1600	=	BD_{soil} (bulk density of soil) from Exhibit 4-3,
15	=	*d* (depth of incorporation for agricultural land) from Exhibit 4-3, and
10^{-1}	=	constant to convert (kg · cm/m^3) to (Mg/ha).

Then, the concentration of manganese in the soil, and thus the earthworm's exposure to manganese, is calculated using Eqs. 4-1 and 4-10:

$$CT_{manganese} = EXPO_{manganese} = \frac{\left(\frac{342\,mg}{kg} \cdot \frac{2400\,Mg}{ha}\right) + \left(20\,yr \cdot \frac{1620\,mg}{kg} \cdot \frac{7\,Mg}{ha\text{-}yr}\right)}{\left(20\,yr \cdot \frac{7\,Mg}{ha\text{-}yr}\right) + \frac{2400\,Mg}{ha}}$$

$$= 410\,mg/kg$$

where:

342	=	BS_j (background concentration of manganese in soil) from Exhibit 4-4,
2400	=	*MS* (mass of soil in agricultural mixing zone), estimated above,
20	=	*N* (total number of years sewage sludge is applied to agricultural land) from Exhibit 4-3,
1620	=	C_j (manganese concentration in sewage sludge) from Exhibit 4-1, and
7	=	*AR* (application rate of sewage sludge to agricultural land) from Exhibit 4-3.

4.2.10 Pathway 10 - Toxicity to Predators of Soil-Dwelling Organisms

Pathway 10 evaluates toxicity to animals feeding on soil-dwelling organisms living in sewage sludge-amended soils on both agricultural and non-agricultural lands. Non-agricultural lands include forests, reclaimed land, and public contact sites. For both the agricultural and non-agricultural Pathway 10, the HEI is a small insectivorous mammal (e.g., shrew or mole), that consumes soil-dwelling organisms. The soil-dwelling organisms considered in this pathway are earthworms.

Methods

For exposure to occur through this pathway, soil-dwelling organisms must bioconcentrate or bioaccumulate pollutants from the sewage sludge-amended soil. For agricultural and reclaimed land, the concentration of pollutant in the soil is calculated using Eq. 4-1 in Section 4.2.1. For forests and public contact sites, it is assumed that there would be no incorporation of land-applied sewage sludge. This implies that the soil layer to which the soil-dwelling organisms are exposed is pure sewage sludge. Therefore, the concentration of each pollutant in the exposure layer ("soil") is set equal to its concentration in the sewage sludge.

Exposure for Pathway 10 is reported in terms of milligrams pollutant per kilogram of diet for the insectivorous mammal, assuming that the only source of the pollutant in the mammal's diet is from ingestion of contaminated soil-dwelling organisms (earthworms). This dietary concentration is referred to as the "pollutant intake level" and is represented by PIL_j in the following equation:

$$EXPA_j = PIL_j = CT_j \cdot BACC_j \cdot FD \qquad (4\text{-}13)$$

where:

$EXPA_j$	=	exposure of insectivorous mammal to pollutant j (mg pollutant/kg diet),
PIL_j	=	intake level of pollutant j in insectivorous mammal's diet (mg pollutant/kg diet),
CT_j	=	concentration of pollutant j in sewage sludge-amended soil (mg pollutant/kg sewage sludge-amended soil),
$BACC_j$	=	bioaccumulation factor for pollutant j (mg pollutant/kg soil organisms per mg pollutant/kg sewage sludge-amended soil), and
FD	=	fraction of diet considered to be soil organisms (unitless, kg soil organisms/kg diet).

First, the concentration of the pollutant in the soil-dwelling prey is calculated by multiplying the pollutant concentration in the soil (CT_j) by a bioaccumulation factor ($BACC_j$). To adjust the pollutant concentration in soil-dwelling organisms to the analogous concentration in the entire diet of the insectivorous mammal, the concentration in the soil-dwelling organisms is then multiplied by the fraction of the insectivorous mammal's diet that consists of soil-dwelling organisms.

Data Inputs

There are two data inputs required for this pathway: fraction of diet considered to be soil organisms and bioaccumulation factors. As in Round One, it is assumed that the fraction of the HEI's diet that is composed of soil-dwelling organisms is one-third, based on a consideration of maximum chronic consumption of earthworms by wildlife (U.S. EPA, 1992a).

Because earthworms are generally the most conspicuous prey item of the soil biota and are considered a potential vector for the transfer of sewage sludge pollutants up the food chain, a number of studies have measured bioaccumulation in earthworms. Most of the studies, however, have been focused on a select set of metals (e.g., cadmium, lead, mercury, selenium, zinc, copper, nickel, and chromium) or persistent chlorinated hydrocarbons, such as DDT (see Beyer, 1990; Gillett, 1994). Very few data were found on bioaccumulation of Round Two candidate pollutants by earthworms from soil.

Bioaccumulation of Organic Pollutants. No empirical data were found on bioaccumulation in soil organisms for any of the candidate organic pollutants for Round Two except dioxins and dibenzofurans. A predictive equation that describes bioaccumulation of all organic compounds in earthworms inhabiting contaminated soils was found (Menzie et al., 1992). This equation is based on a relationship between the fraction of organic carbon in the soil and the lipid content of earthworms:

$$BACC = \frac{Y_1}{0.66 \cdot f_{oc}}$$

where:

$BACC$	=	bioaccumulation factor for earthworms (dimensionless),
Y_1	=	lipid content of earthworms (fraction),
0.66	=	constant derived by Menzie et al., 1992, and
f_{oc}	=	the fraction of organic carbon in the mixing zone of the sewage sludge-amended soil.

The lipid content of earthworms can be assumed to be two percent, as reported in Menzie et al. (1992) for the earthworm *Lumbricus terrestris*. Assuming the fraction of organic carbon in the mixing zone of the sewage sludge-amended soil to be 0.01 (U.S. EPA, 1992a), the bioaccumulation factor in earthworms for all organic pollutants would be 3.0. This value was not used in Round Two, however, because it is not pollutant-specific.

Bioaccumulation of Inorganic Pollutants. Very few studies were found from which bioaccumulation factors for the inorganic Round Two candidate pollutants could be determined. Walton (1987) investigated sodium fluoride accumulation in earthworms (primarily *Lumbricus terrestris*). From the results of one of the experiments, the bioaccumulation factor for worms (including gut contents) in soil with a high level of fluoride was calculated to be 0.670. This value was used for the *BACC* for fluoride.

Helmke et al. (1979) investigated effects of land-applied sewage sludge on the concentration of many different elements in earthworms (*Aporrectodea tuberculata*). Four of the elements measured were candidate Round Two pollutants: antimony, barium, manganese, and thallium. By taking the ratio of the reported concentrations of these metals in earthworms living in the control soil to the concentrations of the metals in the control soil, *BACCs* were calculated for antimony, barium, manganese, and thallium. The authors noted that the earthworms may not have truly accumulated these metals into their tissues. Instead, the concentrations measured were probably due to the metals in the casts (soil in the gut of the worms). However, because predators of earthworms eat entire earthworms, including casts, these bioaccumulation values were considered appropriate for this analysis. Exhibit 4-15 displays the bioaccumulation factors used for the candidate Round Two pollutants. Note that if pollutants do not have data on bioaccumulation, they are not included in the exhibit.

EXHIBIT 4-15
Bioaccumulation Factors for Soil-Dwelling Organisms

Pollutant	Bioaccumulation Factor	Reference
Antimony	0.13	Helmke et al. (1979)
Barium	0.062	Helmke et al. (1979)
Dioxins and Dibenzofurans	10	U.S. EPA (1994a)
Fluoride	0.67	Walton (1987)
Manganese	0.073	Helmke et al. (1979)
Thallium	0.062	Helmke et al. (1979)

Example Exposure Calculation for Pathway 10

The following example estimates exposure of predators of soil-dwelling organisms to manganese in agricultural soil.

First, the mass of soil in the mixing zone, *MS*, is estimated for agricultural land by using Eq. 4-2:

$$MS = \frac{1600kg}{m^3} \cdot 15cm \cdot \frac{10^{-1}Mg/ha}{kg \cdot cm/m^3} = \frac{2400Mg}{ha}$$

where:

1600 = BD_{soil} (bulk density of soil) from Exhibit 4-3,
15 = *d* (depth of incorporation for agricultural land) from Exhibit 4-3, and
10^{-1} = constant to convert (kg · cm/m^3) to (Mg/ha).

The concentration of manganese in the soil is then calculated using Eq. 4-1:

$$CT_{manganese} = \frac{\left(\frac{342mg}{kg} \cdot \frac{2400Mg}{ha}\right) + \left(20yr \cdot \frac{1620mg}{kg} \cdot \frac{7Mg}{ha-yr}\right)}{\left(20yr \cdot \frac{7Mg}{ha-yr}\right) + \frac{2400Mg}{ha}}$$

$$= 410 mg/kg$$

where:

342	=	BS_j (background concentration of manganese in soil) from Exhibit 4-4,
2400	=	MS (mass of soil in agricultural mixing zone), estimated above,
20	=	N (total number of years sewage sludge is applied to agricultural land) from Exhibit 4-3,
1620	=	C_j (manganese concentration in sewage sludge) from Exhibit 4-1, and
7	=	AR (application rate of sewage sludge to agricultural land) from Exhibit 4-3.

The "pollutant intake level" (*PIL*), and thus exposure of the HEI, is then calculated using Eq. 4-13:

$$EXPA_{manganese} = PIL_{manganese} = 410\frac{mg}{kg} \cdot 0.073 \cdot \frac{1}{3}$$
$$= 10\ mg/kg$$

where:

410	=	CT_j (concentration of manganese in agricultural soil), estimated above,
0.073	=	$BACC_j$ (bioaccumulation factor for manganese for soil-dwelling organisms) from Exhibit 4-15, and
⅓	=	FD (fraction of diet that is soil-dwelling organisms), discussed above.

4.2.11 Pathway 11 - Human Toxicity Through Inhalation of Particulates Resuspended by Tilling Sewage Sludge

Pathway 11 evaluates human (tractor operator) exposure to particles that have been resuspended by the tilling of dewatered sewage sludge into the soil. Because this type of exposure is associated only with farming, exposure to sewage sludge applied to non-agricultural land is not evaluated for Pathway 11.

Methods

To calculate the total pollutant concentration in the soil for both organics and inorganics, Eq. 4-1 in Section 4.2.1 is used. To calculate the exposure of the tractor operator to pollutants, the following equation is used:

$$EXPT_j = CT_j \cdot TDA \cdot 10^{-6} \qquad (4\text{-}14)$$

where:

$EXPT_j$ = exposure of tractor operator to pollutant j (mg pollutant/m^3 air),
CT_j = concentration of pollutant j in sewage sludge-amended soil (mg pollutant/kg sewage sludge-amended soil),
TDA = total exposure of tractor operator to soil dust (mg soil dust/m^3 air), and
10^{-6} = constant to convert (kg) to (mg).

Data Inputs

As in Round One, the total dust exposure of the tractor operator is assumed to be the total dust standard of 10 mg/m^3 established by the American Conference of Governmental Industrial Hygienists (ACGIH).

Example Exposure Calculation for Pathway 11

The following example estimates exposure of a tractor operator to manganese.

First, the mass of soil in the mixing zone, *MS*, is estimated for agricultural land by using Eq. 4-2:

$$MS = \frac{1600kg}{m^3} \cdot 15cm \cdot \frac{10^{-1}Mg/ha}{kg \cdot cm/m^3} = \frac{2400Mg}{ha}$$

where:

1600 = BD_{soil} (bulk density of soil) from Exhibit 4-3,
15 = d (depth of incorporation for agricultural land) from Exhibit 4-3, and
10^{-1} = constant to convert (kg $\cdot$ cm/m^3) to (Mg/ha).

The concentration of manganese in the soil is then calculated using Eq. 4-1:

$$CT_{manganese} = \frac{\left(\frac{342mg}{kg} \cdot \frac{2400Mg}{ha}\right) + \left(20yr \cdot \frac{1620mg}{kg} \cdot \frac{7Mg}{ha\text{-}yr}\right)}{\left(20yr \cdot \frac{7Mg}{ha\text{-}yr}\right) + \frac{2400Mg}{ha}}$$

$$= 410 mg/kg$$

where:

342 = BS_j (background concentration of manganese in soil) from Exhibit 4-4,
2400 = *MS* (mass of soil in agricultural mixing zone), estimated above,

20	=	N (total number of years sewage sludge is applied to agricultural land) from Exhibit 4-3,
1620	=	C_j (manganese concentration in sewage sludge) from Exhibit 4-1, and
7	=	AR (application rate of sewage sludge to agricultural land) from Exhibit 4-3.

Using Eq. 4-14, exposure of the tractor operator to manganese is then estimated as:

$$EXPT_{manganese} = 410\frac{mg}{kg} \cdot 10\frac{mg}{m^3} \cdot 10^{-6}\frac{kg}{mg}$$

$$= 4.1x10^{-3}\ mg/m^3$$

where:

410	=	CT_j (concentration of manganese in agricultural soil), estimated above,
10	=	TDA (total exposure of tractor operator to soil dust), discussed above, and
10^{-6}	=	constant to convert (kg) to (mg).

4.2.12 Pathway 12 - Ingestion of Fish and Water from Surface Water that Receives Eroded Soil

Pathway 12 evaluates human ingestion of fish and water from surface water that receives eroded soil from sewage sludge-amended agricultural and non-agricultural lands. Non-agricultural lands include forests, reclamation sites, and public contact sites.

To estimate exposure for this pathway, a mass balance analysis is required. This mass balance analysis accounts for the partitioning of pollutants into different soil phases (solids, air, and water) and the subsequent losses of pollutants from the land application site. Pollutants are lost from a land application site by: erosion of soil particles, which releases sorbed pollutants into surface waters; volatilization of pollutants into air; leaching of pollutants into groundwater; and degradation. A mass balance for a pollutant must be maintained, given these four competing loss processes of erosion, volatilization, leaching, and degradation. Once mass balances for pollutants have been established, exposures to pollutants that have eroded, volatilized, or leached are calculated under three separate pathways: surface water (Pathway 12), air (Pathway 13), and groundwater (Pathway 14). It is assumed that if pollutants degrade, they degrade into chemicals that do not pose unacceptable risks to public health or the environment.

The methods for performing the mass balance calculation for Pathways 12, 13, and 14 are discussed below. Subsequent to this discussion, the equations particular to Pathway 12, for estimating the maximum amount of pollutant available for erosion at a site and the transport of that pollutant mass to a surface water stream, are presented.

Method for Mass Balance (Pathways 12, 13, and 14)

There are two major steps involved in the mass balance calculation. First, a pollutant is partitioned among the three phases present in a soil: solids, air, and water. Second, the rates at which the four loss processes occur (erosion, volatilization, leaching, and degradation) are estimated. These two steps are described in the next two subsections.

Step 1: Partitioning of Pollutant Among Solids, Air, and Water in Sewage Sludge-Amended Soil. This section describes the methods for partitioning a pollutant in the sewage sludge-amended soil at a land application site, assuming that equilibrium is maintained among the pollutant concentration sorbed onto soil particles (which erodes into surface water), the pollutant concentration in the air-filled pore space (which volatilizes), and the pollutant concentration in the porewater (which leaches to groundwater).

Equilibrium partitioning between sorbed and dissolved phases is described by soil-water partition coefficients; partitioning between dissolved and gaseous phases is described by Henry's Law constants. From these assumptions and the definitions of concentrations in different phases presented below, equations are derived to describe pollutant partitioning among all of the phases.

Mathematically, pollutant concentrations in different phases can be expressed as:

$$C_s = \frac{M_{cs}}{M_s} \qquad C_a = \frac{M_{ca}}{V_a} \qquad C_w = \frac{M_{cw}}{V_w} \tag{4-15}$$

and:

$$C_t = \frac{M_{ct}}{V_t} = \frac{M_{cs} + M_{ca} + M_{cw}}{V_s + V_a + V_w} \tag{4-16}$$

where:

C_s = concentration of sorbed pollutant on sewage sludge-amended soil particles (kg pollutant/kg soil),
M_{cs} = mass of sorbed pollutant (kg),
M_s = mass of soil (kg),
V_s = volume of solids in soil (m^3),
C_a = concentration of gaseous pollutant in air-filled pore space of sewage sludge-amended soil (kg pollutant/m^3 air),
M_{ca} = mass of gaseous pollutant (kg),
V_a = volume of air in soil (m^3),
C_w = concentration of dissolved pollutant in water-filled pore space of sewage sludge-amended soil (kg pollutant/m^3 porewater),
M_{cw} = mass of dissolved pollutant (kg),
V_w = volume of water in soil (m^3),
C_t = total concentration of pollutant in bulk sewage sludge-amended soil (kg pollutant/m^3 total bulk soil volume),
M_{ct} = total mass of pollutant in soil (kg), and
V_t = total bulk volume of soil (m^3).

The definitions of equilibrium partition coefficients and soil characteristics, such as bulk density and porosity, are used in conjunction with Eqs. 4-15 and 4-16 to estimate the pollutant concentrations in each soil phase (solids, air, and water). The equilibrium partition or distribution coefficient (K_d), describing the partitioning of a pollutant between pollutant sorbed on solids and pollutant dissolved in porewater, can be defined as:

$$K_d = \frac{[M_{cs}/M_s]}{[M_{cw}/V_w]} \cdot 10^3 = \frac{M_{cs}\ V_w}{M_s\ M_{cw}} \cdot 10^3 \tag{4-17}$$

where:

K_d = soil-water partition coefficient (L water/kg soil), and
10^3 = constant to convert (m^3) to (L).

The dimensionless Henry's Law constant, which describes the partitioning of a pollutant between gaseous and dissolved phases, is defined as:

$$\dot{H} = \frac{[M_{ca}/V_a]}{[M_{cw}/V_w]} = \frac{M_{ca}\ V_w}{M_{cw}\ V_a} \tag{4-18}$$

where:

$\dot{H}$ = Henry's Law constant (dimensionless).

The bulk density of soil is defined as:

$$BD_{mix} = M_s \ / \ V_t \tag{4-19}$$

where:

BD_{mix} = bulk density of sewage sludge-amended soil (kg soil/m^3 total bulk soil volume).

The air-filled porosity of soil is defined as:

$$\theta_a = V_a \ / \ V_t \tag{4-20}$$

where:

θ_a = air-filled porosity (dimensionless).

The water-filled porosity is defined as:

$$\theta_w = V_w \ / \ V_t \tag{4-21}$$

where:

θ_w = water-filled porosity (dimensionless).

And, the total porosity of soil is defined as:

$$\theta_t = (V_t - V_s) \ / \ V_t = \theta_a + \theta_w \tag{4-22}$$

where:

θ_t = total soil porosity (dimensionless).

By combining Eqs. 4-15 through 4-22, equations that describe the pollutant concentrations in the air and water phases in terms of the total pollutant concentration can be derived:

$$C_a = \frac{C_t}{\frac{K_d\ BD_{mix}}{\dot{H}} \cdot 10^{-3} + \frac{\theta_w}{\dot{H}} + \theta_a} \tag{4-23}$$

and:

$$C_w = \frac{C_t}{BD_{mix}\ K_d \cdot 10^{-3} + \theta_w + \dot{H}\ \theta_a} \tag{4-24}$$

Equations 4-23 and 4-24 are used to estimate the first-order rate constants for volatilization and leaching in the second step of the mass balance calculation.

It is important to note that in these derivations, C_t, the total pollutant concentration in sewage sludge-amended soil, is expressed as mass per volume. Recall that in Pathways 1 through 11, the total pollutant concentration is expressed as mass per mass of soil (CT_j). These two quantities can be related through the following equation:

$$C_t = CT_j \cdot BD_{mix} \cdot 10^{-6} \tag{4-25}$$

where:

C_t	=	total concentration of pollutant in bulk sewage sludge-amended soil (kg pollutant/m^3 total bulk soil volume),
CT_j	=	concentration of pollutant j in sewage sludge-amended soil (mg pollutant/kg sewage sludge-amended soil), and
10^{-6}	=	constant to convert (mg) to (kg).

Step 2: Estimating Rates at Which Pollutants Are Lost From Sewage Sludge-Amended Soil. There are four major processes by which a pollutant can be lost from sewage sludge-amended soil: erosion of soil to which the pollutant is sorbed; volatilization of the pollutant; leaching of the pollutant to groundwater; and degradation of the pollutant. These four loss processes are all modeled as being first-order, i.e., the rate at which a pollutant erodes, volatilizes, leaches, or degrades is proportional to the remaining pollutant concentration in the soil. The loss rate coefficients for the four loss processes can be combined to yield a coefficient for the total rate at which the pollutant is lost from sewage sludge-amended soil:

$$K_{tot} = K_{ero} + K_{vol} + K_{lec} + K_{deg} \tag{4-26}$$

where:

K_{tot}	=	total loss rate for the pollutant from sewage sludge-amended land (yr^{-1}),
K_{ero}	=	loss rate due to erosion of the pollutant from sewage sludge-amended land (yr^{-1}),
K_{vol}	=	loss rate due to volatilization of the pollutant from sewage sludge-amended land (yr^{-1}),
K_{lec}	=	loss rate due to leaching of the pollutant from sewage sludge-amended land (yr^{-1}), and
K_{deg}	=	loss rate due to abiotic or microbial degradation of the pollutant on sewage sludge-amended land (yr^{-1}).

The ratio of each individual loss coefficient to the total then describes the fraction of pollutant loss caused by each individual process:

$$f_{ero} = \frac{K_{ero}}{K_{tot}} \qquad f_{vol} = \frac{K_{vol}}{K_{tot}}$$
$$f_{lec} = \frac{K_{lec}}{K_{tot}} \qquad f_{deg} = \frac{K_{deg}}{K_{tot}} \tag{4-27}$$

where:

f_{ero}	=	fraction of total pollutant loss caused by erosion (dimensionless),
f_{vol}	=	fraction of total pollutant loss caused by volatilization (dimensionless),
f_{lec}	=	fraction of total pollutant loss caused by leaching (dimensionless), and
f_{deg}	=	fraction of total pollutant loss caused by degradation (dimensionless).

These fractions are used with the pollutant concentrations in various soil phases to maintain a mass balance of pollutant. In the next four subsections, the calculations for estimating the loss rate coefficients for each individual loss process (erosion, volatilization, leaching, and degradation) are presented.

First-Order Loss Rate for Erosion. Pollutant losses to erosion are approximated by taking the ratio of the average rate of soil loss for the land application site to the depth to which sewage sludge is incorporated, assuming a pollutant is evenly incorporated into the soil. Therefore, the first-order loss rate coefficient for erosion is:

$$K_{ero} \approx \frac{d_e}{d \cdot 10^{-2}} \tag{4-28}$$

where:

d_e	=	average rate of soil loss due to erosion from sewage sludge-amended land each year (m/yr),
d	=	depth of incorporation of sewage sludge (cm), and
10^{-2}	=	constant to convert (cm) to (m).

Note that this assumes that the loss to erosion includes pollutant mass in all three phases (solids, air, and water); therefore, the first-order loss coefficient is not pollutant-specific. That is, given the assumption of even incorporation, if one-tenth of the sewage sludge-soil mixture is removed by erosion, one-tenth of the mass of pollutant is also removed.

First-Order Loss Rate for Volatilization. Estimates of volatile emissions from uncovered soil are used in conjunction with estimates of pollutant concentrations in the air-filled pore space of soil to estimate the loss rate coefficient for volatilization, K_{vol}.

Estimates of volatile emissions are based on equations provided by Hwang and Falco (1986) for contaminated soil with no cover:

$$Na = \frac{2\, t_e\, \theta_e\, D_{ei}\, C_a}{\sqrt{\pi\, \alpha_i\, t_e}} \tag{4-29}$$

where:

Na	=	total average emissions from the soil surface over time interval t_e (kg pollutant/m^2 soil),
t_e	=	duration of emissions (sec),
θ_e	=	effective porosity of soil (dimensionless),
D_{ei}	=	intermediate diffusivity variable (defined in Eq. 4-30) (m^2/sec),
C_a	=	concentration of gaseous pollutant in air-filled pore space of sewage sludge-amended soil (kg pollutant/m^3 air), and
α_i	=	intermediate diffusivity variable (defined in Eq. 4-31) (m^2/sec).

In Hwang and Falco (1986), C_a is estimated from the concentration of sorbed pollutant (C_s). However, this analysis requires the relationship between the <u>total</u> concentration of pollutant in sewage sludge-amended soil (in sorbed, gaseous, and dissolved phases) and the concentration in gaseous phase within the soil's air-filled pore space. Therefore, Eq. 4-23 is used to estimate C_a.

The intermediate diffusivity variables required in Eq. 4-29 are obtained from the following relationships (Hwang and Falco, 1986):

$$D_{ei} = D_{ca} \, 10^{-4} \, \theta_e^{1/3} \tag{4-30}$$

and:

$$\alpha_i = \frac{D_{ei} \, \theta_e}{\theta_e + \rho_{ss} \cdot (1-\theta_e) \cdot K_d \cdot 10^{-3}/\dot{H}} \tag{4-31}$$

where:

$$\rho_{ss} = \frac{BD_{mix}}{(1-\theta_t)} \tag{4-32}$$

and:

$$\dot{H} = \frac{H}{R \cdot T \cdot 10^{-3}} \tag{4-33}$$

and where:

D_{ca}	=	the molecular diffusivity of pollutant in air (cm^2/sec),
10^{-4}	=	constant to convert units from (cm^2) to (m^2),
θ_e	=	effective porosity of soil (dimensionless),
ρ_{ss}	=	particle density of sewage sludge-soil mixture (kg/m^3),
K_d	=	soil-water partition coefficient (L water/kg soil),
$\dot{H}$	=	Henry's Law constant (dimensionless),
BD_{mix}	=	bulk density of sewage sludge-amended soil (kg soil/m^3 total bulk soil volume),
θ_t	=	total soil porosity (dimensionless),
H	=	Henry's Law constant (atm-m^3/mol),
R	=	gas constant (L-atm/mol-K),
T	=	temperature (Kelvin), and
10^{-3}	=	constant to convert (L) to (m^3).

Equation 4-29 provides an estimate of total average emissions from an uncovered layer of soil as a function of both time and the initial concentration of pollutant. For consistency with methods used to estimate losses for other pathways, Eq. 4-29 is evaluated for t_e equal to 1 year (t_e=3.2x10^7 sec), and results are used to estimate an annual loss coefficient. Losses predicted for the first year (Na_y) are divided by the total mass of pollutant in soil to estimate the approximate fraction of available pollutant lost per unit of time. For a unit concentration (1 kg/m^3) of the pollutant in soil (i.e., C_t), the mass of pollutant beneath one square meter of soil surface (in kg/m^2) is equal to the volume of treated soil beneath a square meter of surface (m^3

per m^2), that is, equal to the depth of incorporation (m). The estimated loss rate (in kg/m^2-yr) is approximated as a comparable first-order loss coefficient (in yr^{-1}) as:

$$K_{vol} \approx -\ln\left(1 - \frac{Na_y}{d \cdot 10^{-2}}\right) \tag{4-34}$$

where:

K_{vol}	=	loss rate due to volatilization (yr^{-1}),
Na_y	=	total average emissions from the soil surface in first year (kg pollutant/m^2), estimated using Eq. 4-29,
d	=	depth of incorporation of sewage sludge (cm. When converted to (m), equivalent to kg/m^2 for a unit concentration of pollutant in sewage sludge-amended soil), and
10^{-2}	=	constant to convert (cm) to (m).

Because Eq. 4-29 was derived by assuming the column of soil is of infinite depth, it can predict greater than 100 percent loss within a year for a relatively shallow layer of treated soil and a relatively volatile pollutant. For such cases, Eq. 4-34 cannot be evaluated and the loss rate coefficient is instead estimated from predicted emissions in the first second (t_e=1 sec). The loss rate coefficient estimated from the first second of emissions is then converted to an annual loss rate coefficient:

$$K_{vol} \approx -3.2\times10^{7} \ln\left(1 - \frac{Na_s}{d \cdot 10^{-2}}\right) \tag{4-35}$$

where:

Na_s	=	emissions from the soil surface in first second (kg pollutant/m^2), estimated using Eq. 4-29,
3.2x10^7	=	constant to convert (sec^{-1}) to (yr^{-1}), and
10^{-2}	=	constant to convert (cm) to (m).

Equation 4-34 was used to evaluate carbon disulfide, dioxins and dibenzofurans, endosulfan, pentachloronitrobenzene, PCBs, and 2-(2,4,5-trichlorophenoxy) propionic acid. However, for the other Round Two pollutants that volatilize, Eq. 4-35 was used.

First-Order Loss Rate for Leaching. To estimate pollutant loss to leaching, the following equation, which computes a first-order loss rate for a pollutant leaching from treated soil (U.S. EPA, 1989f), was modified to take into account that leaching is only one of four competing pollutant loss processes:

$$K_{lec} = \frac{NR}{BD_{mix} \cdot K_d \cdot 10^{-3} \cdot d \cdot 10^{-2}} \tag{4-36}$$

where:

K_{lec} = loss rate due to leaching of the pollutant from sewage sludge-amended land (yr^{-1}),

NR = annual recharge to groundwater beneath the treated soil (m^3 recharge/m^2 area-yr, or m recharge/yr),

BD_{mix} = bulk density of sewage sludge-amended soil (kg soil/m^3 total bulk soil volume),

K_d = soil-water partition coefficient (L water/kg soil),

d = depth of incorporation of sewage sludge (cm),

10^{-3} = constant to convert (L) to (m^3), and

10^{-2} = constant to convert (cm) to (m).

To derive a coefficient for first-order loss to leaching while maintaining a mass balance, the mass of pollutant expected to be lost each year is estimated and divided by the available mass of pollutant. The mass of pollutant that will be lost to leaching in any interval of time per unit area (i.e., the flux of pollutant) can be described by the volume of water percolating through the treated soil multiplied by the average concentration of pollutant in that water:

$$FA_{lec} = NR \cdot C_{lec} \cdot 10{,}000 \tag{4-37}$$

where:

FA_{lec} = annual average flux of pollutant leached from sewage sludge-amended soil (kg pollutant/ha-yr),

C_{lec} = concentration of pollutant in water leaching from sewage sludge-amended soil (kg pollutant/m^3 porewater), and

10,000 = constant to convert units from (kg/m^2-yr) to (kg/ha-yr).

Assuming that all the porewater forms leachate, Eq. 4-24 can be used to estimate the pollutant concentration in the leachate:

$$C_w = C_{lec} = \frac{C_t}{\left[BD_{mix} \cdot K_d \cdot 10^{-3} + \theta_w + \dot{H}\,\theta_a\right]} \tag{4-38}$$

where:

C_w = concentration of dissolved pollutant in water-filled pore space of sewage sludge-amended soil (kg pollutant/m^3 porewater),

C_t = total concentration of pollutant in bulk sewage sludge-amended soil (kg pollutant/m^3 total bulk soil volume),

θ_w = water-filled porosity (dimensionless),

$\dot{H}$	=	Henry's Law constant (dimensionless),
θ_a	=	air-filled porosity (dimensionless), and
10^{-3}	=	constant to convert (L) to (m^3).

Given that first-order loss rates are being assumed, the total concentration of pollutant in soil decreases due to leaching according to the following equation:

$$\frac{dC_t}{dt} = -K_{lec} C_t \tag{4-39}$$

K_{lec} can be estimated with the discrete approximation:

$$K_{lec} = \frac{\left[\frac{dC_t}{dt}\right]}{C_t} \approx \frac{\left[\frac{\Delta C_t}{\Delta t}\right]}{C_t} \approx \frac{\left[\frac{\Delta M_{ct}}{\Delta t}\right]}{M_{ct}} \tag{4-40}$$

where:

t	=	time (yr).

The change in the total pollutant mass in the soil with time can be expressed in terms of the pollutant flux leaching to the groundwater:

$$\frac{\Delta M_{ct}}{\Delta t} = FA_{lec} \cdot A \cdot 10^{-4} \tag{4-41}$$

where:

$\Delta M_{ct}/\Delta t$	=	change in total mass of pollutant in soil over time interval of one year (kg/yr),
A	=	area of land application site (m^2), and
10^{-4}	=	constant to convert units from (m^2) to (ha).

Combining Eqs. 4-40 and 4-41:

$$K_{lec} \approx \frac{FA_{lec} \cdot A \cdot 10^{-4}}{M_{ct}} \tag{4-42}$$

Given that the total bulk volume of sewage sludge-amended soil equals the area of the land application site multiplied by the depth of incorporation:

$$V_t = A \cdot d \cdot 10^{-2}$$

where:

V_t = total bulk volume of soil (m^3),

and rearranging Eq. 4-16:

$$C_t \cdot V_t = M_{ct}$$

the following equation can be written:

$$\frac{A}{M_{ct}} = \frac{1}{C_t\, d \cdot 10^{-2}} \tag{4-43}$$

Using Eqs. 4-37, 4-38, and 4-43, Eq. 4-42 can be rewritten as:

$$K_{lec} \approx \frac{NR\ C_{lec}}{C_t\, d \cdot 10^{-2}} \approx \frac{NR}{\left[BD_{mix} \cdot K_d + \theta_w + \dot{H}\ \theta_a\right] d \cdot 10^{-2}} \tag{4-44}$$

Equation 4-44 is used to predict the rate of pollutant loss to leaching.

First-Order Loss Rate for Degradation. Values of K_{deg} are obtained from the literature for each pollutant. For K_{deg}, rates of abiotic reactions such as hydrolysis are preferentially used because they can be more reliably measured; for pollutants only degraded by microbes, the lowest aerobic rates measured under environmental conditions are used. For inorganics and some persistent organic pollutants such as dioxins and dibenzofurans, K_{deg} is zero.

Methods Specific to Pathway 12

Overview of Methods Specific to Pathway 12. To calculate the average concentration of a pollutant in eroding soil, estimates of the maximum mass of pollutant available for erosion from a land application site are combined with estimates of the rate at which the pollutant is lost from the site due to the four loss processes over a human lifetime. The average concentration of pollutant in eroded, sewage sludge-amended soil is then "diluted" by the erosion of clean soil from the remainder of the watershed. Estimates of the concentration of pollutants in the stream receiving the eroded soil are then made, derived from the mass of pollutant on eroded soil and on soil-water partition coefficients. Pollutants then partition into fish inhabiting the stream. Humans are exposed to pollutants through both direct ingestion of surface water and ingestion of fish. For this analysis, organics as well as inorganics are allowed to build up in the soil over the active life of the land application site.

Maximum Pollutant Mass Available for Erosion. The maximum mass of pollutant available for erosion at a land application site occurs after the final application of sewage sludge to the site. This maximum mass is estimated as:

$$TP_N = AR \cdot C_j \cdot \left(1 + e^{-c \cdot K_{tot}} + e^{-2c \cdot K_{tot}} + \ldots + e^{-b \cdot c \cdot K_{tot}}\right) \cdot 1000 \cdot 1 \qquad (4\text{-}45)$$

where:

TP_N	=	total mass of pollutant available at a site after the final year of application (mg pollutant/ha),
AR	=	annual whole sludge application rate of sewage sludge to land (dry Mg sewage sludge/ha-yr),
C_j	=	concentration of pollutant j in sewage sludge (mg pollutant/kg sewage sludge),
c	=	application interval (number of years between applications),
K_{tot}	=	total loss rate for the pollutant from sewage sludge-amended land (yr^{-1}),
b	=	model parameter that is equal to the integer part of $((N_{site}-1)/c)$, where N_{site} is the site life (yr),
1000	=	constant to convert (Mg) to (kg), and
1	=	interval of time over which pollutant loss is evaluated (yr).

Losses to Erosion Averaged Over a Human Lifetime. Because human exposure is assumed to continue for the duration of an individual's lifetime, concentrations of pollutants in surface water are calculated based on losses of pollutant through surface erosion for a period equal to the human life expectancy. Therefore, loss to erosion during the period between the end of land application and the end of an individual's lifetime must be estimated. To do so, the mass of pollutant left at the end of an individual lifetime is first calculated. After the last application of sewage sludge to a site, a pollutant continues to be depleted according to the following equation:

$$M_{LS} = TP_N \cdot e^{-K_{tot}(LS - N_{site})} \qquad (4\text{-}46)$$

where:

M_{LS}	=	mass of pollutant in soil at end of a period equal to an individual lifetime (mg pollutant/ha),
LS	=	average human lifetime (yr), and
N_{site}	=	site life (yr).

The fraction of total, cumulative loading lost to all four loss processes in the human lifetime (over both the application and post-application periods) can then be calculated as:

$$f_{LS} = \frac{(N \cdot C_j \cdot AR \cdot 1000) - M_{LS}}{N \cdot C_j \cdot AR \cdot 1000} \tag{4-47}$$

where:

f_{LS} = fraction of total cumulative loading lost in individual's lifetime to all four loss processes (dimensionless).

This fraction is used to estimate the average pollutant concentration in eroded soil for both organic and inorganic pollutants. The estimated total loading of pollutant is multiplied by the fraction expected to be lost to erosion in the human lifetime ($f_{ero} \cdot f_{LS}$), and divided by the total mass of eroded soil lost during that period to calculate the expected average concentration of each pollutant in eroded soil:

$$C_{site,\,j} = \frac{N \cdot C_j \cdot AR \cdot 1000 \cdot f_{ero} \cdot f_{LS}}{ME_{site} \cdot LS} \tag{4-48}$$

where:

$C_{site,\,j}$ = the concentration of pollutant j in sewage sludge-amended soil eroded from the land application site (mg pollutant/kg sewage sludge-amended soil),

ME_{site} = rate of soil loss for land treated with sewage sludge (kg sewage sludge-amended soil/ha-yr), and

$$ME_{site} = d_e \cdot BD_{mix} \cdot 10{,}000 \tag{4-49}$$

where:

d_e = average rate of soil loss due to erosion from sewage sludge-amended land each year (m/yr),

BD_{mix} = bulk density of sewage sludge-amended soil (kg soil/m^3 total bulk soil volume), and

10,000 = constant to convert (m^2) to (ha).

Note that Eq. 4-48 assumes that the same mass of pollutant leaves the site by erosion every year.

Dilution of Eroded, Sewage Sludge-Amended Soil with Non-Sewage Sludge-Amended Soil. The extent to which eroded soil from the land application site is "diluted" by soil from the untreated remainder of the watershed also needs to be estimated. A "dilution factor" describes the fraction of the total eroded soil in the watershed originating in the land application site:

$$D_f = \frac{A_{site}\ ME_{site}\ S_{site}}{\left[A_{site}\ ME_{site}\ S_{site}\right] + \left[\left(A_{ws} - A_{site}\right) ME_{ws}\right] S_{ws}} \tag{4-50}$$

where:

D_f	=	dilution factor (dimensionless),
A_{site}	=	area of land application site (ha),
A_{ws}	=	area of the watershed (ha),
S_{site}	=	sediment delivery ratio for the land application site (dimensionless),
S_{ws}	=	sediment delivery ratio for the watershed (dimensionless), and
ME_{ws}	=	estimated rate of soil loss (erosion) for the watershed (kg soil/ha-yr).

If the rates of soil erosion from the land application site and the remainder of the watershed are assumed to be the same, ME_{site} and ME_{ws} cancel from Eq. 4-50, and the dilution factor can be calculated by:

$$D_f = \frac{A_{site}\ S_{site}}{A_{site}\ S_{site} + \left[\left(A_{ws} - A_{site}\right) S_{ws}\right]} \tag{4-51}$$

The sediment delivery ratios for the land application site and the watershed are calculated with the following empirical relationship (Vanoni, 1975):

$$S = 0.872\ A^{-0.125}$$

Thus, the sediment delivery ratio for the site and for the watershed are:

$$S_{site} = 0.872\ [A_{site}]^{-0.125} \tag{4-52}$$

and

$$S_{ws} = 0.872\ [A_{ws}]^{-0.125} \tag{4-53}$$

If all of a pollutant entering the stream on eroded soil is assumed to originate from the land application site, the dilution factor, D_f, also describes the ratio between the average concentration of pollutant in soil entering the stream and the average concentration in soil eroding from the land application site:

$$C_{esoil,\,j} = D_f \cdot C_{site,\,j} \tag{4-54}$$

where:

$C_{esoil,j}$ = dry weight concentration of pollutant j in eroded soil entering the stream (mg pollutant/kg eroded soil).

Pollutant Concentration in the Stream. The estimated concentration of pollutant in the eroded soil is used as an input to calculate the expected concentration of pollutant in the stream. Once the eroded soil enters the stream, the pollutant is assumed to partition between the solid and liquid phases of the stream according to equilibrium conditions. The total amount of pollutant available to partition depends on the amount of eroded soil in the stream. Assuming that all of the total suspended solids in the stream are from eroded soil particles, Eq. 4-55 partitions the total mass of pollutant between dissolved and sorbed phases. The lefthand term represents the total mass of pollutant (per liter of water) entering the stream in eroded soil; the middle term represents the dissolved pollutant; and, the right-most term represents the mass of sorbed pollutant (per liter of water):

$$C_{esoil,j} \cdot TSS \cdot 10^{-6} = C_{sw,j} + \left(C_{sw,j} \cdot K_d \cdot TSS \cdot 10^{-6}\right) \tag{4-55}$$

where:

TSS = concentration of total suspended solids in the stream (mg solids/L water),
$C_{sw,j}$ = concentration of pollutant j in surface water (mg pollutant/L water),
K_d = soil-water partition coefficient (L water/kg soil), and
10^{-6} = constant to convert (mg) to (kg).

Solving Eq. 4-55 for the concentration of pollutant dissolved in the stream:

$$C_{sw,j} = \frac{C_{esoil,j} \cdot TSS \cdot 10^{-6}}{1 + K_d \cdot TSS \cdot 10^{-6}} \tag{4-56}$$

Partition Coefficients for Organic Pollutants. For organic pollutants, a partition coefficient between water and suspended solids (K_d) is estimated from each pollutant's organic carbon-water partition coefficient (K_{oc}) and an assumption about the fraction of organic carbon (f_{oc}) on suspended solids in streams:

$$K_d = K_{oc} \cdot f_{oc} \tag{4-57}$$

where:

K_{oc} = organic carbon-water partition coefficient (mL water/g organic carbon), and

f_{oc} = fraction of organic carbon in suspended solids (dimensionless, g organic carbon/g suspended solids).

A value of 0.01 is used for the f_{oc} of suspended solids, to correspond to the f_{oc} of the mixing zone from which the suspended solids are assumed to have eroded (U.S. EPA, 1993a).

To estimate an organic pollutant's K_{oc} value, an empirical regression equation presented by Hasset et al. (1983) is used:

$$\log_{10}(K_{oc}) = 0.088 + 0.909 \log_{10}(K_{ow}) \tag{4-58}$$

where:

K_{ow} = octanol-water partition coefficient (dimensionless, mg pollutant/L octanol per mg pollutant/L water).

Partition Coefficients for Inorganic Pollutants. For inorganic pollutants, it is much more difficult to predict a "typical" K_d value. Metals can sorb onto soils through the processes of ion exchange, specific adsorption, co-precipitation with hydrous oxides, and incorporation into cationic lattice sites in crystalline sediments (Bodek et al., 1988). Therefore, clay minerals, organic matter, and manganese and iron oxides are all important sorbents of metals in soil (Bodek et al., 1988). The pH of the system also affects metal sorption, with most metals tending to sorb more at higher pHs. Therefore, measured K_d values reported in the literature for conditions similar to those being modeled are used.

Estimating Human Exposure

Humans can be exposed to surface water contaminated by sewage sludge through two pathways: ingestion of water and ingestion of fish. Potential exposure through ingestion of contaminated surface water is calculated as:

$$EXP_{w,j} = \frac{C_{sw,j} \cdot IW}{BW} \tag{4-59}$$

where:

$EXP_{w,j}$ = exposure to pollutant j through direct ingestion of surface water (mg pollutant/kg body weight-day),

$C_{sw,j}$	=	concentration of pollutant j in surface water (mg pollutant/L water),
IW	=	quantity of water ingested daily (L water/day), and
BW	=	body weight (kg), assumed to be 70 kg.

Exposure through ingestion of fish is calculated based on estimates of the bioaccumulation of a pollutant in fish and the assumed rate of fish ingestion. Bioaccumulation is the process by which aquatic organisms accumulate pollutants, from both water and food, at concentrations higher than the ambient concentration. The process by which a pollutant is absorbed from water through gill membranes or other external body surfaces is called bioconcentration, and the measure of a pollutant's tendency to bioconcentrate is described by the bioconcentration factor. For organic pollutants, a regression equation based on $\log(K_{ow})$ values is used to estimate bioconcentration factors (BCFs). The equation was developed for a three percent lipid content of fish (U.S. EPA, 1990):

$$\log_{10}(BCF) = 0.79 \log_{10}(K_{ow}) - 0.80 \tag{4-60}$$

where:

BCF	=	pollutant-specific bioconcentration factor (L water/kg fish).

For inorganic pollutants, available literature values were used for BCFs.

Biomagnification denotes the process by which the concentration of a pollutant increases in different organisms occupying successive trophic levels. The combined accumulation from bioconcentration and biomagnification is represented by the bioaccumulation factor, which is calculated as the product of the bioconcentration factor and a food chain multiplier:

$$BAF = BCF \cdot FM \tag{4-61}$$

where:

BAF	=	pollutant-specific bioaccumulation factor (L water/kg fish), and
FM	=	pollutant-specific food chain multiplier (dimensionless).

Assuming that humans only ingest fish fillets, and not the whole fish, the pollutant concentration in fish fillets can be expressed as:

$$C_{ff,j} = C_{sw,j} \cdot BAF \cdot P_f \tag{4-62}$$

where:

$C_{ff,j}$	=	concentration of pollutant j in fish fillets (mg pollutant/kg fish fillet), and

P_f = ratio of pollutant concentration in fillet to whole fish (dimensionless).

Thus, human exposure through ingestion of contaminated fish can be expressed as:

$$EXP_{f,j} = \frac{C_{ff,j} \cdot IF}{BW} \qquad (4\text{-}63)$$

where:

$EXP_{f,j}$ = exposure to pollutant j through ingestion of fish (mg pollutant/kg body weight-day), and

IF = daily consumption of fish fillets (kg fish fillets/day).

For this analysis of the surface water pathway, exposures through drinking water consumption and fish ingestion are combined:

$$EXP_j = EXP_{w,j} + EXP_{f,j} \qquad (4\text{-}64)$$

where:

EXP_j = exposure to pollutant j through consumption of both surface water and fish combined (mg pollutant/kg body weight-day).

Data Inputs

Both non-pollutant-specific and pollutant-specific inputs are required for the exposure equations described above. Values for non-pollutant-specific inputs, such as the area of a watershed, its hydrogeological characteristics, and the daily consumption of fish and drinking water, are presented in Exhibit 4-16. Note that all parameters necessary for Pathways 12, 13, and 14 are presented in this Exhibit.

There are several pollutant-specific fate and transport parameters required to maintain the mass balance of a pollutant among the four loss processes and to estimate the rates at that those four loss processes occur. In Exhibit 4-17, all of the fate and transport parameters are presented.

To obtain estimates of inorganic K_d values for six Round Two pollutants, studies of adsorption described in Gerritse et al. (1982) were used. Gerritse et al. present a range of K_d values for various inorganics in two soil types: sand and sandy loam. In the sandy soil, there was 0.035 g/g organic matter, 0 g/g clay, 0.22 meq/g cation exchange capacity (CEC), and the porewater had a pH of 5. In the sandy loam soil, there was 0.025 g/g organic matter, 0.2 g/g clay, 0.16 meq/g CEC, and the porewater had a pH of 8. For this analysis, the K_d values from sand, which were lower than those in sandy loam, were used. In addition, the lowest K_d value from the range available for each of the six Round Two inorganics tested was used.

For aluminum and fluoride, available data on Langmuir isotherm parameters were used to estimate K_d values (Bodek et al., 1988). For aluminum, data were for silica, at a pH of 5. For fluoride, data corresponded to clay loam, containing 10.4 percent clay, 0.94 percent organic carbon, and 825 μg/g aluminum, with a pH of 5.9. For boron, thallium, tin, and titanium, K_d values were not available.

In the absence of pollutant-specific data for the ratio of pollutant concentration in fillet to the concentration in whole fish, it is assumed that these concentrations are the same ($P_f = 1$) for all pollutants except PCBs and dioxins. PCBs are assumed to behave similarly to dioxins, for which a ratio of 0.5 has been estimated (Branson et al., 1985).

For *BCF* values for inorganic pollutants, the Ambient Aquatic Life Water Quality Criteria documents were reviewed. Only three Round Two inorganics had such documents available: aluminum, antimony, and silver. For aluminum, bioconcentration factors for young brook trout were reported to range from 50 to 231 (U.S. EPA, 1988a). The geometric mean (107) was used in this analysis. For antimony, one study on bioconcentration in bluegill found no significant accumulation above controls (U.S. EPA, 1988b). AQUIRE (Aquatic Toxicity Information Retrieval) was then searched for *BCF* data on antimony. The AQUIRE run turned up values for one saltwater fish and one fish that may or may not be saltwater. The *BCF*s for the shanny (*Blennius pholis*) and for the two-spot goby (*Gobiusculus flavescens*) are 0.40 and 0.15, respectively. The geometric mean of these two values (0.24) was used in this analysis. For silver, the Ambient Aquatic Life Water Quality Criteria for Silver document (U.S. EPA, 1987) had *BCF* information for two freshwater fish species, bass and bluegill. The geometric mean of the bass *BCF*s (11 and 19) is 14; the geometric mean of the bluegill *BCF*s (15 and 150) is 47. The geometric mean of the two species' *BCF*s is 26; this value was used in this analysis.

AQUIRE was then searched for all the remaining inorganics (Ba, Be, B, F, Mn, Th, Sn, Ti, and V). No data on *BCF* values for freshwater fish were found.

For *FM* values, if an organic pollutant had a $\log(K_{ow})$ value less than or equal to five, a value of one was used; otherwise a value of ten was used for *FM* (U.S. EPA, 1990). This relationship is applicable to a species on a trophic level of three. For inorganic pollutants, an *FM* value of one was used.

EXHIBIT 4-16
Non-Pollutant-Specific Parameters for Pathways 12, 13, and 14

Parameter	Definition	Value	Reference
θ_t	total soil porosity	0.4 (dimensionless)	U.S. EPA, 1992a
θ_e	effective soil porosity	0.4 (dimensionless)	U.S. EPA, 1992a
θ_a	air-filled porosity	0.2 (dimensionless)	U.S. EPA, 1992a
θ_w	water-filled porosity	0.2 (dimensionless)	U.S. EPA, 1992a
A_{site}	area of land treated with sewage sludge	1,074 ha	U.S. EPA, 1992a
A_{ws}	area of watershed	440,300 ha	U.S. EPA, 1992a
c	application interval	varies	See N in Exhibit 4-3
d_e	yearly depth of soil eroded	6×10^{-4} m/yr	USDA, 1987
NR	annual recharge to groundwater	0.5 m/yr	U.S. EPA, 1992a
ρ_w	density of water	1 kg/L	approximate density of water under environmental conditions
TSS	total suspended solids in surface water	16 mg/L	U.S. EPA, 1992a
θ	angle subtended by the land application site's width	22.5°	U.S. EPA, 1992a
u	average wind velocity	4.5 m/sec	U.S. EPA, 1992a
v	vertical dispersion of pollutant in air	1 (dimensionless)	U.S. EPA, 1992a
T	average air temperature	288 Kelvin	U.S. EPA, 1992a
IF	daily consumption of fish fillets	0.04 kg/day	U.S. EPA, 1992a
IA	daily inhalation rate	20 m^3/day	U.S. EPA, 1992a
IW	daily ingestion of water	2 L/day	U.S. EPA, 1992a
N_{site}	site life	20 yr ag., forest, pub., 1 yr recl.	
R	gas constant	0.082 L-atm/mol-Kelvin	constant

EXHIBIT 4-17
Environmental Fate and Transport Parameters

Pollutant	log K_{ow}	K_d (L/kg)	Henry's Law Constant[1] (atm-m^3/mol)	K_{deg} (yr^{-1})[2]	Diffusivity in Air (D_{ca})[1] (cm^2/sec)	Diffusivity in Water (D_{cw})[1] (cm^2/sec)	BCF (L/kg)	FM
Acetic acid (2,4-dichlorophenoxy)	2.81[3]	4.4[4]	1.4×10^{-10} [5]	36[6]	5.5×10^{-2}	4.9×10^{-6}	26[7]	1
Aluminum	NA	4[8]	NA	NA	NA	NA	79[9]	1
Antimony	NA	6[10]	NA	NA	NA	NA	0.25[11]	1
Barium	NA	6[10]	NA	NA	NA	NA		1
Beryllium	NA	43[10]	NA	NA	NA	NA		1
Bis(2-ethylhexyl) phthalate	5.11[12]	540[4]	8.8×10^{-6} [13]	11[14]	3.4×10^{-2}	2.9×10^{-6}	1700[7]	10
Boron	NA		NA	NA	NA	NA		1
Butanone, 2-	0.29[16]	0.022[4]	5.8×10^{-5} [17]	25[18]	9.2×10^{-2}	7.8×10^{-6}	0.27[7]	1
Carbon disulfide	2.00[19]	0.81[4]	1.4×10^{-2} [20]	0.006[21]	1.1×10^{-1}	9.7×10^{-6}	6.0[7]	1
Cresol, p-	1.94[3]	0.71[4]	7.9×10^{-7} [22]	380[14]	7.4×10^{-2}	6.6×10^{-6}	5.4[7]	1
Cyanides (soluble salts and complexes)	-1.04[23]	0.0014[4]	1.2×10^{-4} [24]	13[24]	1.9×10^{-1}	1.8×10^{-5}	0.02[7]	1
Dioxins and Dibenzofurans	6.64[25]	13,000[4]	6.8×10^{-5} [25]	0[25]	4.4×10^{-2}	4.1×10^{-6}	27,900[7]	10

EXHIBIT 4-17
Environmental Fate and Transport Parameters (cont'd.)

Pollutant	log K_{ow}	K_d (L/kg)	Henry's Law Constant[1] (atm-m^3/mol)	K_{deg} (yr^{-1})[2]	Diffusivity in Air (D_{ca})[1] (cm^2/sec)	Diffusivity in Water (D_{cw})[1] (cm^2/sec)	BCF (L/kg)	FM
Endosulfan-II	3.52[26]	19[4]	1.9×10^{-5} [27]	6.7[28]	4.3×10^{-2}	3.6×10^{-6}	96[7]	1
Fluoride	NA	36[8]	NA	NA	NA	NA		1
Manganese	NA	0.9[10]	NA	NA	NA	NA		1
Methylene chloride	1.3[29]	0.19[4]	2.0×10^{-3} [27]	2.6[30]	1.0×10^{-1}	9.2×10^{-6}	1.7[7]	1
Pentachloronitrobenzene	4.64[3]	200[4]	9.9×10^{-5} [31]	1.1[32]	5.2×10^{-2}	4.9×10^{-6}	730[7]	1
Phenol	1.46[33]	0.26[4]	4.0×10^{-7} [22]	72[34]	8.2×10^{-2}	7.4×10^{-6}	2.3[7]	1
Polychlorinated biphenyls (coplanar)	6.7[35]	15,000[4]	2.0×10^{-4} [36]	0.063[37]	4.5×10^{-2}	4.1×10^{-6}	31,000[7]	10
Propanone, 2-	-0.24[3]	0.0074[4]	3.7×10^{-5} [38]	36[14]	1.1×10^{-1}	9.1×10^{-6}	0.10[7]	1
Propionic acid, 2-(2,4,5-trichlorophenoxy)	3.41[3]	15[4]	1.3×10^{-8} [39]	17[40]	4.9×10^{-2}	4.4×10^{-6}	78[7]	1
Silver	NA	290[10]	NA	NA	NA	NA	25[41]	1
Thallium	NA		NA	NA	NA	NA		1
Tin	NA		NA	NA	NA	NA		1
Titanium	NA		NA	NA	NA	NA		1

EXHIBIT 4-17
Environmental Fate and Transport Parameters (cont'd.)

Pollutant	log K_{ow}	K_d (L/kg)	Henry's Law Constant[1] (atm-m^3/mol)	K_{deg} (yr^{-1})[2]	Diffusivity in Air (D_{ca})[1] (cm^2/sec)	Diffusivity in Water (D_{cw})[1] (cm^2/sec)	BCF (L/kg)	FM
Toluene	2.79[27]	4.2[4]	6.7×10^{-3} [27]	120[42]	8.0×10^{-2}	6.9×10^{-6}	25[7]	1
Trichlorophenoxy acetic acid, 2,4,5-	3.13[3]	8.6[4]	9.4×10^{-11} [43]	13[15]	5.4×10^{-2}	4.6×10^{-6}	47[7]	1
Vanadium	NA	39[10]	NA	NA	NA	NA		1

Notes:
NA means Not Applicable
1 Discussed in Sections 4.2.13 and 4.2.14.
2 Aerobic degradation rate.
3 Hansch and Leo (1985a).
4 Estimated using Eqs. 4-57 and 4-58.
5 Jury et al. (1987).
6 Ou (1984).
7 Estimated using Eq. 4-60.
8 Based on Langmuir isotherm data in Bodek et al. (1988).
9 U.S. EPA (1988a).
10 Low value from K_d range measured for that inorganic in sand in Gerritse et al. (1982). See text for details.
11 U.S. EPA (1988b).
12 CHEMEST procedure of GEMS, U.S. EPA (1989c).
13 Howard et al. (1985); Montgomery and Welkom (1990).
14 Howard et al. (1991).
15 Smith (1978, 1979); McCall et al. (1981); Alton and Stritzke (1973).
16 Hansch and Leo (1981).
17 Rathburn and Tai (1987).
18 Dojlido (1979); Price et al. (1974); Bridie et al. (1979); Dose et al. (1975); Heukelekian and Rand (1955).
19 Verschueren (1983).

[20] Elliot (1989).
[21] Peyton et al. (1976).
[22] Hine and Mookerjee (1975).
[23] Estimated from Lyman et al. (1990) for hydrogen cyanide.
[24] Bodek et al. (1988).
[25] U.S. EPA (1994b).
[26] OHM/TADS (1989).
[27] Mabey et al. (1982).
[28] Greve and Wit (1971).
[29] Hansch and Leo (1979).
[30] Davis and Madsen (1991).
[31] Calculated from water solubility (Eckert, 1962) and vapor pressure (Gile and Gillett, 1979).
[32] Wang and Broadbent (1972).
[33] Hansch and Leo (1985b).
[34] Baker and Mayfield (1980).
[35] Based on Aroclor 1254 from O'Connor (1992) and Anderson and Parker (1990).
[36] Murphy et al. (1987).
[37] Fries (1982).
[38] Snider and Dawson (1985).
[39] Howard, 1991.
[40] Smith (1978); Alton and Stritzke (1973).
[41] U.S. EPA (1987).
[42] Wilson et al. (1983).
[43] Based on water solubility (Klopffer et al., 1982) and vapor pressure (Que Hee et al., 1981).

Example Exposure Calculations for Pathway 12

The following example calculates exposure of humans to dioxins and dibenzofurans through ingestion of water and fish from surface water receiving eroded sewage sludge-amended soil from agricultural land.

Step 1: Partitioning of Pollutant

In Step 1 of the mass balance calculation, relationships among pollutant concentrations in the bulk sewage sludge-amended soil (C_t), in the air-filled pore space (C_a), and in the water-filled pore space (C_w) are derived. In this example calculation, these relationships are used to estimate K_{vol} and K_{lec} in Step 2.

Step 2: Estimation of K_{ero}

Equation 4-28 can be used to calculate the loss rate coefficient for erosion (K_{ero}):

$$K_{ero} = \frac{6x10^{-4}\ m/yr}{15\ cm \cdot 10^{-2}\ m/cm} = 4x10^{-3}\ yr^{-1}$$

where:

$6x10^{-4}$	=	d_e (average rate of soil loss due to erosion from sewage sludge-amended land each year) from Exhibit 4-16,
15	=	d (depth of incorporation for sewage sludge on agricultural land) from Exhibit 4-3, and
10^{-2}	=	constant to convert (cm) to (m).

Step 2: Estimation of K_{vol}

Several equations are used to calculate the loss rate coefficient for volatilization (K_{vol}). First, the intermediate diffusivity variable D_{ei} is calculated from Eq. 4-30:

$$D_{ei} = 4.4x10^{-2}\ cm^2/\text{sec} \cdot 10^{-4}\ m/cm^2 \cdot (0.4)^{1/3} = 3.2x10^{-6}\ m^2/\text{sec}$$

where:

$4.4x10^{-2}$	=	D_{ca} (diffusivity of pollutant in air) from Exhibit 4-17,
10^{-4}	=	factor to convert (cm^2) to (m^2), and
0.4	=	θ_e (effective porosity of soil) from Exhibit 4-16.

Second, the particle density of the sewage sludge-soil mixture (ρ_{ss}) is calculated using Eq. 4-32:

$$\rho_{ss} = \frac{1400\ kg/m^3}{(1\ -\ 0.4)} = 2.3x10^3 kg/m^3$$

where:

1400	=	BD_{mix} (bulk density of sewage sludge-amended soil) from Exhibit 4-3, and
0.4	=	θ_t (total porosity of soil) from Exhibit 4-16.

Third, the dimensionless Henry's Law constant ($\dot{H}$) is calculated using Eq. 4-33:

$$\dot{H} = \frac{6.8x10^{-5} atm\text{-}m^3/mol}{(0.082\ L\text{-}atm/mol\text{-}K) \cdot 288K \cdot 0.001\ m^3/L}$$
$$= 2.9x10^{-3}$$

where:

$6.8x10^{-5}$	=	H (Henry's Law constant) from Exhibit 4-17,
0.082	=	R (universal gas constant) from Exhibit 4-16,
288	=	T (average air temperature in Kelvin) from Exhibit 4-16, and
0.001	=	factor to convert (L) to (m^3).

Fourth, the intermediate diffusivity variable α_i is calculated from Eq. 4-31:

$$\alpha_i = \frac{3.2x10^{-6}\ m^2/\text{sec} \cdot 0.4}{0.4 + \dfrac{2.3x10^3\ kg/m^3 \cdot (1-0.4) \cdot 13{,}000\ L/kg}{2.9x10^{-3} \cdot 1000\ L/m^3}}$$
$$= 2.0x10^{-13} m^2/\text{sec}$$

where:

$3.2x10^{-6}$	=	D_{ei} (calculated above),
0.4	=	θ_e (effective porosity of soil) from Exhibit 4-16,
$2.3x10^3$	=	ρ_{ss} (calculated above),
13,000	=	K_d (partition coefficient for dioxins between water and soil) from Exhibit 4-17,
$2.9x10^{-3}$	=	$\dot{H}$ (calculated above), and
1000	=	constant to convert (m^3) to (L).

Next, to calculate C_a, Eq. 4-23 is used with a unit concentration of $1 kg/m^3$ for C_t:

$$C_a = \frac{1\ kg/m^3}{\frac{[13{,}000\ L/kg \cdot 1400\ kg/m^3 \cdot 0.001\ m^3/L]}{2.9x10^{-3}} + \frac{0.2}{2.9x10^{-3}} + 0.2}$$

$$= 1.6x10^{-7}\ kg/m^3$$

where:

1	=	C_t (unit concentration of pollutant in bulk sewage sludge-amended soil),
13000	=	K_d (soil-water partition coefficient) from Exhibit 4-17,
1400	=	BD_{mix} (bulk density of sewage sludge-amended soil) from Exhibit 4-3,
0.001	=	constant to convert (L) to (m^3),
$2.9x10^{-3}$	=	$\dot{H}$ (dimensionless Henry's Law constant) calculated above,
0.2	=	θ_w (water-filled porosity) from Exhibit 4-16, and
0.2	=	θ_a (air-filled porosity) from Exhibit 4-16.

Total average emissions from the soil surface in one year are then calculated using Eq. 4-29:

$$Na_y = \frac{2 \cdot 31{,}536{,}000\ \sec \cdot 0.4 \cdot 3.2x10^{-6}\ m^2/\sec \cdot 1.6x10^{-7}\ kg/m^3}{\sqrt{\pi \cdot 2.0x10^{-13}\ m^2/\sec \cdot 31{,}536{,}000\ \sec}}$$

$$= 2.9x10^{-3} kg/m^2$$

where:

31,536,000	=	t_e (duration of emissions), corresponding to one year,
0.4	=	θ_e (effective porosity of soil) from Exhibit 4-16,
$3.2x10^{-6}$	=	D_{ei} (intermediate diffusivity variable) calculated above,
$1.6x10^{-7}$	=	C_a (concentration of dioxins in air-filled pore space) calculated above, and
$2.0x10^{-13}$	=	α_i (intermediate diffusivity variable) calculated above.

Finally, K_{vol} can be calculated using Eq. 4-34:

$$K_{vol} \approx -\ln\left[1 - \frac{2.9x10^{-3}}{0.15\ kg/m^2}\right] \approx 1.9x10^{-2}yr^{-1}$$

where:

$2.9x10^{-3}$	=	Na_y (total average emissions from the soil surface in the first year), calculated above, and
0.15	=	d (depth of incorporation of sewage sludge) from Exhibit 4-3; see text for explanation of why this may be expressed as a mass per area.

Step 2: Estimation of K_{lec}

Equation 4-44 can be used to approximate the loss rate coefficient for leaching (K_{lec}):

$$K_{lec} \approx \frac{0.5\ m/yr}{[1400\ kg/m^3 \cdot 13{,}000\ L/kg \cdot 0.001\ m^3/L + 0.2 + 2.9x10^{-3} \cdot 0.2] \cdot 0.15\ m}$$

$$\approx 1.8x10^{-4}\ yr^{-1}$$

where:

0.5	=	NR (annual recharge to ground water) from Exhibit 4-16,
1400	=	BD_{mix} (bulk density of sewage sludge-amended soil) from Exhibit 4-3,
13,000	=	K_d (soil-water partition coefficient) from Exhibit 4-17,
0.001	=	constant to convert (L) to (m^3),
0.2	=	θ_w (water-filled porosity) from Exhibit 4-16,
0.2	=	θ_a (air-filled porosity) from Exhibit 4-16,
$2.9x10^{-3}$	=	$\dot{H}$ (dimensionless Henry's law constant) calculated above, and
0.15	=	d (depth of incorporation of sewage sludge) from Exhibit 4-3.

Step 2: Estimation of K_{tot}

The total loss rate for dioxins from the sewage sludge-amended agricultural land is calculated from Eq. 4-26:

$$K_{tot} = 4x10^{-3}\ yr^{-1} + 1.9x10^{-2}\ yr^{-1} + 1.8x10^{-4}\ yr^{-1} + 0\ yr^{-1}$$

$$= 2.3x10^{-2}\ yr^{-1}$$

where:

$4x10^{-3}$	=	K_{ero} (loss coefficient for erosion) calculated above,
$1.9x10^{-2}$	=	K_{vol} (loss coefficient for volatilization) calculated above,
$1.8x10^{-4}$	=	K_{lec} (loss coefficient for leaching) calculated above, and
0	=	K_{deg} (loss coefficient for degradation) from Exhibit 4-17.

Maximum Pollutant Mass Available for Erosion

Once K_{tot} is calculated, it is then used in Eq. 4-45 to calculate the maximum mass of pollutant onsite:

$$TP_N = \frac{7\ Mg}{ha\text{-}yr} \cdot 3.11x10^{-4}\ \frac{mg}{kg} \cdot \left(1 + e^{-1 \cdot 2.3x10^{-2}} + ... + e^{-19 \cdot 1 \cdot 2.3x10^{-2}}\right) \cdot 1000\ \frac{kg}{Mg} \cdot 1yr$$

$$= 35\ mg/ha$$

where:

7	=	AR (application rate) from Exhibit 4-3,
$3.11x10^{-4}$	=	C_j (concentration of dioxins in sewage sludge) from Exhibit 4-1,
1	=	c (application interval) from Exhibit 4-3,
$2.3x10^{-2}$	=	K_{tot} (total loss rate for dioxins) calculated above,
19	=	b (equal to integer part of $(N\text{-}1)/c$, where N is the site life), from Exhibit 4-3,
1000	=	constant to convert (Mg) to (kg), and
1	=	interval of time over which pollution loss is evaluated.

To calculate the mass of pollutant left in the sewage sludge-amended soil at the end of an individual's lifetime, Eq. 4-46 is used:

$$M_{LS} = 35\ mg/ha \cdot e^{-(2.3x10^{-2} yr^{-1}) \cdot (70yr - 20yr)}$$

$$= 11\ mg/ha$$

where:

35	=	TP_N (total mass of dioxins available at a site after the final year of application) calculated above,

$2.3x10^{-2}$	=	K_{tot} (total loss rate for dioxins) calculated above,
70	=	LS (average human lifetime), assumed to be 70 yr, and
20	=	N_{site} (site life) from Exhibit 4-3.

Then, f_{LS} can be calculated using Eq. 4-47:

$$f_{LS} = \frac{\left(20\ yr \cdot 3.11x10^{-4}\ \frac{mg}{kg} \cdot \frac{7\ Mg}{ha\text{-}yr} \cdot 1000\ \frac{kg}{Mg}\right) - 11\frac{mg}{ha}}{20\ yr \cdot 3.11x10^{-4}\ \frac{mg}{kg} \cdot \frac{7\ Mg}{ha\text{-}yr} \cdot 1000\ \frac{kg}{Mg}}$$

$$= 0.75$$

where:

20	=	N (number of years sewage sludge is applied to land) from Exhibit 4-3,
$3.11x10^{-4}$	=	C_j (concentration of dioxins in sewage sludge) from Exhibit 4-1,
7	=	AR (application rate) from Exhibit 4-3,
1000	=	constant to convert (Mg) to (kg), and
11	=	M_{LS} (mass of dioxins in soil at end of period equal to an individual's lifetime) calculated above.

Pollutant Concentration on Eroded Soil

The expected average concentration of pollutant on soil eroding from the land application site ($C_{site,\ j}$) requires two additional parameters to be calculated. First, the fraction of total pollutant loss caused by erosion is calculated by Eq. 4-27:

$$f_{ero} = \frac{4x10^{-3}\ yr^{-1}}{2.3x10^{-2}\ yr^{-1}} = 0.17$$

where:

$4x10^{-3}$	=	K_{ero} (loss coefficient for erosion) calculated above, and
$2.3x10^{-2}$	=	K_{tot} (total loss rate for dioxins) calculated above.

Second, the calculated rate of soil loss for a land application site is calculated using Eq. 4-49:

$$ME_{site} = 6x10^{-4} \ m/yr \cdot 1400 \ kg/m^3 \cdot 10{,}000 \ m^2/ha$$

$$= 8400 \ kg/ha\text{-}yr$$

where:

$6x10^{-4}$	=	d_e (average rate of soil loss due to erosion from sewage sludge-amended land each year) from Exhibit 4-16,
1400	=	BD_{mix} (bulk density of sewage sludge-amended soil) from Exhibit 4-3, and
10,000	=	constant to convert (ha) to (m^2).

Then, $C_{site,j}$ can be calculated using Eq. 4-48:

$$C_{site,dioxins} = \frac{20 \ yr \cdot 3.11x10^{-4} \ \frac{mg}{kg} \cdot 7 \ \frac{Mg}{ha\text{-}yr} \cdot 1000 \ \frac{kg}{Mg} \cdot 0.17 \cdot 0.75}{8400 \ \frac{kg}{ha\text{-}yr} \cdot 70 \ yr}$$

$$= 9.5x10^{-6} \ \frac{mg}{kg}$$

where:

20	=	N (number of years sewage sludge is applied to land) from Exhibit 4-3,
$3.11x10^{-4}$	=	C_j (concentration of dioxins in sewage sludge) from Exhibit 4-1,
7	=	AR (application rate) from Exhibit 4-3,
1000	=	constant to convert (Mg) to (kg),
0.17	=	f_{ero} (fraction of total pollutant loss caused by erosion) calculated above,
0.75	=	f_{LS} (fraction of total cumulative loading lost in individual's lifetime to all four loss processes) calculated above,
8400	=	ME_{site} (rate of soil loss) calculated above, and
70	=	LS (lifetime of an individual), assumed to be 70 years.

A dilution factor, to represent the extent to which eroded soil from the land application site is "diluted" by soil from the untreated remainder of the watershed, is calculated using Eq. 4-51. First, the sediment delivery ratios for the land application site and watershed are calculated using Eqs. 4-52 and 4-53:

$$S_{site} = 0.872 \cdot (1074\ ha)^{-0.125} = 0.36$$
$$S_{ws} = 0.872 \cdot (440{,}300\ ha)^{-0.125} = 0.17$$

where:

1074	=	A_{site} (area of land application site treated with sewage sludge) from Exhibit 4-16, and
440,300	=	A_{ws} (area of the watershed) from Exhibit 4-16.

Then the dilution factor is calculated using Eq. 4-51:

$$D_f = \frac{1074\ ha \cdot 0.36}{(1074\ ha \cdot 0.36) + [(440{,}300\ ha - 1074\ ha) \cdot 0.17]}$$

$$= 5.2x10^{-3}$$

where:

0.36	=	S_{site} (sediment delivery ratio for land treated with sludge) calculated above, and
0.17	=	S_{ws} (sediment delivery ratio for the watershed) calculated above.

The dry weight concentration of pollutant in eroded soil ($C_{esoil,\,j}$) can be calculated using Eq. 4-54:

$$C_{esoil,dioxins} = 5.2x10^{-3} \cdot 9.5x10^{-6} \frac{mg}{kg}$$

$$= 4.9x10^{-8}\ \frac{mg}{kg}$$

where:

$5.2x10^{-3}$	=	D_f (dilution factor) calculated above, and
$9.5x10^{-6}$	=	$C_{site,\,j}$ (concentration of dioxins in sewage sludge-amended soil eroded from the land application site) calculated above.

Equation 4-56 is then used to calculate the concentration of pollutant dissolved in the surface water:

$$C_{sw,dioxins} = \frac{4.9x10^{-8}\ mg/kg \cdot 16\ mg/L \cdot 10^{-6}\ kg/mg}{1 + 13{,}000\ L/kg \cdot 16\ mg/L \cdot 10^{-6}\ kg/mg}$$

$$= 6.5x10^{-13}\ mg/L$$

where:

$4.9x10^{-8}$	=	$C_{esoil,\ j}$ (dry weight concentration of dioxins in eroded soil) calculated above,
16	=	*TSS* (concentration of total suspended solids in the surface water) from Exhibit 4-16,
13,000	=	K_d (soil-water partition coefficient for dioxins in the stream) from Exhibit 4-17, and
10^{-6}	=	constant to convert (mg) to (kg).

Exposure Calculations

Potential human exposure to dioxins through direct ingestion of surface water is calculated using Eq. 4-59:

$$EXP_{w,dioxins} = \frac{6.5x10^{-13}\ mg/L \cdot 2\ L/day}{70\ kg}$$

$$= 1.8x10^{-14}\ mg/kg\text{-}day$$

where:

$6.5x10^{-13}$	=	$C_{sw,\ j}$ (concentration of dioxins in surface water) calculated above,
2	=	*IW* (ingestion rate of water) from Exhibit 4-16, and
70	=	*BW* (body weight), assumed to be 70 kg.

Potential human exposure to dioxins through consumption of contaminated fish is calculated using Eqs. 4-60 through 4-63. First, the *BCF* for dioxins is calculated using Eq. 4-60:

$$\log_{10}(BCF) = 0.79 \cdot 6.64 - 0.80 = 4.4$$

where:

6.64 = $\log_{10}(K_{ow})$ from Exhibit 4-17.

The BAF is calculated using Eq. 4-61:

$$BAF = 28{,}000 \cdot 10 = 2.8x10^{5}$$

where:

28,000	=	BCF (bioconcentration factor for dioxins) calculated above by exponentiating $\log_{10}(BCF)$, and
10	=	FM (food chain multiplier for dioxins) from Exhibit 4-17.

The concentration of dioxins in fish fillets is then calculated from Eq. 4-62:

$$C_{ff,j} = 6.5x10^{-13}\ mg/L \cdot 2.8x10^{5}\ L/kg \cdot 0.5$$

$$= 9.0x10^{-8}\ mg/kg$$

where:

$6.5x10^{-13}$	=	$C_{sw,j}$ (concentration of dioxins in surface water) calculated above,
$2.8x10^{5}$	=	BAF (bioaccumulation factor for dioxins) calculated above, and
0.5	=	P_f (ratio of pollutant concentration in fillet to whole fish) from Data Inputs.

Human exposure through ingestion of fish fillets is then calculated using Eq. 4-63:

$$EXP_{f,dioxins} = \frac{9.0x10^{-8}\ mg/kg \cdot 0.04\ kg/day}{70\ kg}$$

$$= 5.2x10^{-11}\ mg/kg\text{-}day$$

where:

$9.0x10^{-8}$	=	$C_{ff,j}$ (concentration of dioxins in fish fillets) calculated above,
0.04	=	IF (daily ingestion of fish) from Exhibit 4-16, and
70	=	BW (body weight), assumed to be 70 kg.

Total exposure to dioxins in surface water is the sum of the exposures to dioxins in water and fish, as shown in Eq. 4-64:

$$EXP_{dioxins} = 1.8x10^{-14}\ mg/kg\text{-}day + 5.2x10^{-11} mg/kg\text{-}day$$

$$= 5.2x10^{-11}\ mg/kg\text{-}day$$

where:

$1.8x10^{-14}$	=	$EXP_{w,j}$ (exposure to dioxins through ingestion of surface water), calculated above, and
$5.2x10^{-11}$	=	$EXP_{f,j}$ (exposure to dioxins through ingestion of fish) calculated above.

4.2.13 Pathway 13 - Inhalation of Pollutants Volatilized from Land-Applied Sewage Sludge

Pathway 13 evaluates human exposure to pollutants volatilizing from both agricultural and non-agricultural lands to which sewage sludge has been applied. Non-agricultural lands include forests, reclamation sites, and public contact sites.

To estimate exposure for this pathway, a mass balance analysis is required. This mass balance analysis accounts for the partitioning of pollutants into different soil phases (solids, air, and water) and the subsequent losses of pollutants from the land application site. Pollutants are lost from a land application site by: erosion of contaminated soil particles, which releases pollutants into surface waters; volatilization of pollutants into air; leaching of pollutants into groundwater; and degradation. A mass balance for a pollutant must be maintained, given these four competing loss processes of erosion, volatilization, leaching, and degradation. Once mass balances for pollutants have been established, exposures to pollutants that have eroded, volatilized, or leached are calculated under three separate pathways: surface water (Pathway 12), air (Pathway 13), and groundwater (Pathway 14). Pollutants which have degraded are assumed to have degraded into chemicals that do not pose unacceptable risks to public health or the environment.

The methods for performing the mass balance calculation for Pathways 12, 13, and 14 are discussed in Section 4.2.12. In this section, the equations particular to Pathway 13, for estimating the pollutant mass expected to volatilize and its transport to the downwind edge of the land application site, are presented. Note that volatilization is assumed to occur within a one-year period; any contribution to volatilization from sewage sludge applied in prior years is considered negligible.

Methods Specific to Pathway 13

There are two major steps required to estimate the concentration of a volatilized pollutant in air at the downwind edge of the land application site:

1) Using the mass balance calculations presented in Section 4.2.12, the mass of pollutant expected to volatilize from the land application site within a period equivalent to a human lifespan is estimated.

2) Using a simplified version of the Industrial Source Complex Long Term Model (ISCLT), the transport and dispersion of pollutant in ambient air at the downwind edge of the land application site are modeled.

In the first step, the rate at which a pollutant volatilizes from the site is estimated, based on the assumption that equilibrium has been achieved between annual pollutant loadings and total losses:

$$FA_{vol,j} = 0.001 \cdot AR \cdot C_j \cdot f_{vol} \qquad (4\text{-}65)$$

where:

$FA_{vol,j}$	=	annual average flux of pollutant j volatilizing from the sewage sludge-amended soil (kg pollutant/ha-yr),
0.001	=	constant to convert units from (Mg-mg/kg) to (kg),
AR	=	annual whole sludge application rate of sewage sludge to land (dry Mg sewage sludge/ha-yr),
C_j	=	concentration of pollutant j in sewage sludge (mg pollutant/kg sewage sludge), and
f_{vol}	=	fraction of total pollutant loss caused by volatilization (dimensionless).

The fraction of total pollutant loss caused by volatilization is obtained from the mass balance calculation presented in Section 4.2.12.

In the second step, pollutant concentrations in ambient air at the downwind edge of the land application site are estimated, based on pollutant fluxes from the site. The model used to simulate transport of pollutants from treated land is described by U.S. EPA (1986d) and is based on equations provided by Environmental Science and Engineering (1985). These equations are simplifications of equations used in ISCLT.

The exposed individual is assumed to live within 1 km of the land application site and to be exposed to concentrations present at the downwind edge of the land application site. A source-receptor ratio is calculated to relate the concentration of pollutant in ambient air at that individual's location (g/m^3) to the rate at which that pollutant is emitted from the treated soil (g/m^2-sec):

$$SRR = 2.032 \frac{A_{site} \cdot v \cdot 10{,}000}{(r' + x_y) \cdot u \cdot \sigma_z} \tag{4-66}$$

where:

SRR	=	source-receptor ratio (sec/m),
2.032	=	empirical constant,
A_{site}	=	area of land application site (ha),
v	=	vertical term for dispersion of pollutant in air (dimensionless),
10,000	=	constant to convert (ha) to (m^2),
r'	=	distance from center of the land application site to the downwind edge (m),
x_y	=	lateral virtual distance to land application site (m),
u	=	average wind speed (m/sec), and
σ_z	=	standard deviation of the vertical distribution of pollutant concentration in air (m).

The vertical term (v) is a function of source height, the mixing layer height and σ_z. Under stable conditions the mixing layer height is assumed infinite, and for a pollutant release height of zero, $v=1$. The lateral virtual distance is the distance from a virtual point source to the land application site, such that the angle θ subtended by the site's width is 22.5°. This distance is calculated as:

$$x_y = \sqrt{\frac{A_{site} \cdot 10{,}000}{\pi}} \cot \frac{\theta}{2} \tag{4-67}$$

The distance from the center of the land application site to the downwind edge is calculated assuming a square land application site:

$$r' = \frac{\sqrt{A_{site} \cdot 10{,}000}}{2} \tag{4-68}$$

The standard deviation of the vertical distribution of concentration (σ_z) is defined by an atmospheric stability class and the distance from the center of the site to the downwind edge. Exhibit 4-18 provides values for two parameters, a and b, for a range of distances under stable atmospheric conditions. Based on values from this table, an appropriate value of σ_z is calculated as:

$$\sigma_z = a\, x^b \tag{4-69}$$

where:

$$x = 10^{-3} \cdot r' \tag{4-70}$$

and:

x = distance from the center of the land application site to the downwind edge (km), and

10^{-3} = constant to convert (m) to (km).

EXHIBIT 4-18
Parameters Used to Calculate σ_z Under Stable Conditions[1,2]

x (km)	a	b
0.10 - 0.20	15.209	0.81558
0.21 - 0.70	14.457	0.78407
0.71 - 1.00	13.953	0.68465
1.01 - 2.00	13.953	0.63227
2.01 - 3.00	14.823	0.54503
3.01 - 7.00	16.187	0.46490
7.01 - 15.00	17.836	0.41507
15.01 - 30.00	22.651	0.32681
30.01 - 60.00	27.084	0.27436
> 60.00	34.219	0.21716

[1] Environmental Science and Engineering, 1985.
[2] σ_z calculated as $\sigma_z = ax^b$, where x is distance in km.

Once the source-receptor ratio has been estimated, it is combined with the estimated average flux of pollutant to predict the average concentration of pollutant in ambient air at the downwind edge of the site:

$$C_{air,j} = FA_{vol,j} \cdot SRR \cdot 0.00317 \tag{4-71}$$

where:

$C_{air,j}$	=	average concentration of pollutant j in ambient air at the downwind edge of the site (μg pollutant/m^3 air), and
0.00317	=	constant to convert (kg/ha-yr) to ($\mu g/m^2$-sec).

Estimating Human Exposure

The estimated concentrations of pollutants in air are converted to estimates of human exposure based on assumptions about the rate at which the average individual inhales air:

$$EXP_j = \frac{10^{-3} \cdot C_{air,j} \cdot IA}{BW} \tag{4-72}$$

where:

EXP_j	=	exposure to pollutant j in sewage sludge (mg pollutant/kg body weight-day),
10^{-3}	=	constant to convert (μg) to (mg),
$C_{air,j}$	=	average concentration of pollutant j in ambient air (μg pollutant/m^3 air),
IA	=	inhalation rate (m^3 air/day), and
BW	=	body weight (kg).

Data Inputs

All the non-pollutant-specific data inputs required for this pathway are presented in Exhibit 4-16 and all the pollutant-specific parameters are presented in Exhibit 4-17, both in Section 4.2.12. As shown in Exhibit 4-16, the daily inhalation rate for humans is assumed to be 20 m^3/day, the average wind velocity is assumed to be 4.5 m/sec, and the average air temperature is assumed to be 288 K.

Example Exposure Calculations for Pathway 13

The following example calculates exposure of humans to dioxins and dibenzofurans through inhalation of dioxins volatilized from sewage sludge-amended soil on agricultural land. The mass balance portion of the calculation, which is the same for Pathways 12, 13, and 14, is presented in the section "Example Exposure Calculations for Pathway 12". In the mass balance calculation, f_{vol} is estimated from Eq. 4-27:

$$f_{vol} = \frac{1.9x10^{-2}/yr}{2.3x10^{-2}/yr} = 0.82$$

where:

1.9 x 10^{-2}	=	K_{vol} (loss rate due to volatilization of dioxins from sewage sludge-amended land) calculated in Pathway 12, and
2.3 x 10^{-2}	=	K_{tot} (total loss rate for dioxins from sewage sludge-amended land) calculated in Pathway 12.

Equation 4-65 is used to estimate the annual average flux of dioxins volatilizing from sewage sludge-amended land:

$$FA_{vol,dioxins} = 0.001 \cdot 7 Mg/ha\text{-}yr \cdot 3.11x10^{-4} mg/kg \cdot 0.82$$

$$= 1.8x10^{-6} kg/ha\text{-}yr$$

where:

0.001	=	constant to convert (Mg-mg/kg) to (kg),
7	=	AR (annual whole sludge application rate of sewage sludge to land) from Exhibit 4-3,
3.11x10^{-4}	=	C_j (concentration of dioxins in sewage sludge) from Exhibit 4-1, and
0.82	=	f_{vol} (fraction of total pollutant loss caused by volatilization) calculated above.

The source-receptor ratio is then calculated by Eq. 4-66. Three variables, x_y, r', and σ_z, must first be estimated. The lateral virtual distance to the land application site, x_y, is calculated using Eq. 4-67:

$$x_y = \sqrt{\frac{1074\,ha \cdot 10{,}000 m^2/ha}{\pi}} \cdot \cot\frac{22.5}{2}$$
$$= 9295\ m$$

where:

1074	=	A_{site} (area of land application site treated with sewage sludge) from Exhibit 4-16,
10,000	=	constant to convert (ha) to (m^2), and
22.5	=	θ (the angle subtended by the site's width) from Exhibit 4-16.

The standard deviation of the vertical distribution of concentration (σ_z) is then calculated using Eqs. 4-68 through 4-70. The distance from the center of the land application site to the downwind edge is calculated using Eq. 4-68:

$$r' = \frac{\sqrt{1074\,ha \cdot 10{,}000}}{2} = 1639\,m$$

where:

1074	=	A_{site} (area of land application site treated with sewage sludge) from Exhibit 4-16, and
10000	=	constant to convert (ha) to (m^2).

The distance from the center of the land application site to the downwind edge is then converted to kilometers using Eq. 4-70:

$$x = 10^{-3}\ km/m \cdot 1639\,m = 1.6\ km$$

where:

10^{-3}	=	constant to convert (m) to (km), and
1639	=	r' (distance from center of the land application site to the downwind edge) calculated above.

Then the standard deviation of the vertical distribution is calculated using Eq. 4-69:

$$\sigma_z = 13.953 \cdot 1.6^{0.63227} = 19m$$

where:

13.953	=	a (corresponding to x = 1.6 km) from Exhibit 4-18, and
0.63227	=	b (corresponding to x = 1.6 km) from Exhibit 4-18.

The source-receptor ratio can then be calculated using Eq. 4-66:

$$SRR = 2.032 \cdot \frac{1074ha \cdot 1 \cdot 10{,}000}{(1639m + 9295m) \cdot 4.5m/\sec \cdot 19m}$$
$$= 23\sec/m$$

where:

2.032	=	empirical constant,
1074	=	A_{site} (area of land application site treated with sewage sludge) from Exhibit 4-16,
1	=	v (vertical dispersion term) from Exhibit 4-16,
10000	=	constant to convert (ha) to (m^2),
1639	=	r' (distance from center of the land application site to the downwind edge) calculated above,
9295	=	x_y (lateral virtual distance to land application site) calculated above,
4.5	=	u (wind speed) from Exhibit 4-16, and
19	=	σ_z (standard deviation of the vertical distribution of concentration in air) calculated above.

The concentration of dioxins in air ($C_{air,j}$) at the downwind edge of the site can then be calculated using Eq. 4-71:

$$C_{air,dioxins} = 1.8x10^{-6}kg/ha\text{-}yr \cdot 23\sec/m \cdot 0.00317$$
$$= 1.3x10^{-7}\mu g/m^3$$

where:

$1.8x10^{-6}$	=	$FA_{vol,j}$ (annual average flux of dioxins volatilizing from the treated land) calculated above,
23	=	SRR (source-receptor ratio) calculated above, and
0.00317	=	constant to convert (kg/ha-yr) to ($\mu g/m^2$-sec).

Potential human exposure to dioxins through inhalation of dioxins volatilizing from sewage sludge-amended land is calculated from Eq. 4-72:

$$EXP_{dioxins} = \frac{10^{-3} \cdot 1.3x10^{-7} \mu g/m^3 \cdot 20 m^3/day}{70 kg}$$

$$= 3.8x10^{-11} mg/kg\text{-}day$$

where:

10^{-3}	=	constant to convert (μg) to (kg),
$1.3x10^{-7}$	=	$C_{air,j}$ (average concentration of dioxins in ambient air) calculated above,
20	=	*IA* (daily inhalation volume) from Exhibit 4-16, and
70	=	*BW* (body weight), assumed to be 70 kg.

4.2.14 Pathway 14 - Ingestion of Groundwater Containing Leached Pollutants

Pathway 14 evaluates human exposure to pollutants through ingestion of groundwater that receives leachate from agricultural and non-agricultural lands to which sewage sludge has been applied. Non-agricultural lands include forests, reclamation sites, and public contact sites.

To estimate exposure for this pathway, a mass balance analysis is required. This mass balance analysis accounts for the partitioning of pollutants into different soil phases (solids, air, and water) and the subsequent losses of pollutants from the land application site. Pollutants are lost from a land application site by: erosion of contaminated soil particles, which releases pollutants into surface waters; volatilization of pollutants into air; leaching of pollutants into groundwater; and degradation. A mass balance for a pollutant must be maintained, given these four competing loss processes of erosion, volatilization, leaching, and degradation. Once mass balances for pollutants have been established, exposures to pollutants that have eroded, volatilized, or leached are calculated under three separate pathways: surface water (Pathway 12), air (Pathway 13), and groundwater (Pathway 14). Pollutants which have degraded are assumed to have degraded into chemicals that do not pose unacceptable risks to public health or the environment.

The methods for performing the mass balance calculation for Pathways 12, 13, and 14 are discussed in Section 4.2.12. In this section, the equations particular to Pathway 14, for estimating the concentration of pollutant in leachate from a site and modeling the transport of that pollutant to the groundwater, are presented.

Methods Specific to Pathway 14

There are two steps required to estimate the concentration of each pollutant in groundwater near the land application site:

1) Determine the concentration of pollutant in water leaching through the treated soil.

2) Use mathematical models for the transport of pollutant through the unsaturated and saturated soil zones to estimate expected concentrations of pollutant in groundwater.

The maximum mass of pollutant available for leaching from a site is estimated first. For all organic pollutants, except dioxins and dibenzofurans and coplanar PCBs, it is assumed that pollutant concentrations gradually increase in the soil until the rates of annual loss equal the rates of annual loading, and steady-state is achieved. At steady-state, the rate at which the organic pollutant leaches from the site can be determined from the annual loading (which equals total annual losses) and the fraction of total losses attributable to leaching:

$$FA_{lec,j} = AR \cdot C_j \cdot f_{lec} \cdot 0.001 \tag{4-73}$$

where:

$FA_{lec,j}$ = annual average flux of pollutant j leaching from sewage sludge-amended soil (kg pollutant/ha-yr),
AR = annual whole sludge application rate of sewage sludge to land (dry Mg sewage sludge/ha-yr),
C_j = concentration of pollutant j in sewage sludge (mg pollutant/kg sewage sludge),
f_{lec} = fraction of total pollutant loss caused by leaching (dimensionless), and
0.001 = constant for converting units from (Mg-mg/kg) to (kg).

For inorganic pollutants, dioxins and dibenzofurans, and coplanar PCBs, sewage sludge is assumed to be applied over a 20 year period, followed by an inactive period. During the inactive period, pollutant is depleted from the treated soil by leaching and erosion, and for the two classes of organic pollutants, volatilization and degradation as well. To simulate potential contamination of groundwater, the loading of pollutant into the unsaturated zone is "linearized" into a pulse of constant magnitude to represent the maximum annual loss of pollutant (in kg/ha-yr) occurring over the 300-year simulation period modeled. The duration of that pulse is calculated so that pollutant mass is conserved. For land application sites, the maximum rate of loss is expected in the year immediately following the last application of sewage sludge, because the concentration of pollutant at the site reaches its peak at that time. As explained in Appendix C, this peak loss rate could be maintained for a maximum length of time described by:

$$TP = \frac{N}{[1 - e^{(-K_{tot}N)}]} \tag{4-74}$$

where:

TP	=	duration of "square wave" for approximating the loading of pollutant into the unsaturated soil zone (yr), and
N	=	total number of years sewage sludge is applied to land (yr).

This result is combined with an estimate of the fraction of total pollutant loss to leaching for a conservative estimate of the average flux of pollutant leaching from the land application site:

$$FA_{lec,j} = \frac{N \cdot AR \cdot C_j \cdot f_{lec} \cdot 0.001}{TP} \tag{4-75}$$

The fraction of total pollutant loss caused by leaching is obtained from the mass balance calculation presented in Section 4.2.12.

For both organic and inorganic pollutants, the estimated flux from either Eq. 4-73 or Eq. 4-75 can be combined with the assumed rate of net recharge to groundwater at the land application site to derive an estimate of the average concentration of pollutant in the leachate:

$$C_{lec,j} = \frac{0.1 \ FA_{lec,j}}{NR} \tag{4-76}$$

where:

$C_{lec,j}$	=	average concentration of pollutant j in water leaching from the sewage sludge-amended soil (mg pollutant/L water),
0.1	=	constant to convert units from (kg/ha-m) to (mg/L), and
NR	=	annual recharge to groundwater beneath the treated soil (m recharge/yr).

Next, the leachate concentration is used to estimate the concentration of pollutant in drinking water wells near the site. Two mathematical models are combined to calculate an expected ratio between these two concentrations. The Vadose Zone Flow and Transport finite element module (VADOFT) from the RUSTIC model (U.S. EPA, 1989d,g) is used to estimate flow and transport through the unsaturated zone, and the AT123D analytical model (Yeh, 1981) is used to estimate pollutant transport through the saturated zone.